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Renewable energy expansion in the Chilean power market: A dynamic general equilibrium modeling approach to determine CO2 emission baselines

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ABSTRACT

Over the last decade, a high dependency on carbon-intensive fuels in the Chilean power sector has led to environmental concerns, particularly regarding rapid growth in CO2 emissions. More recently, the power sector has experienced significant structural changes with a rapid expansion of renewables in the energy matrix, and this trend is expected to cause significant variations in future CO2-emission baseline scenarios. To investigate the economy-wide impact of renewable energy expansions in Chile's energy mix, this research, based on a Computable General Equilibrium (CGE) model, examines different CO2 emission baseline scenarios. However, because traditional CGE modeling approaches cannot capture the impact of a sector's recent structural changes, we present a step-by-step approach to incorporate different energy matrices from an external engineering bottom-up model into the CGE model. The results indicate that the Business as Usual (BAU) scenario, in which structural changes are not considered, significantly overstates expected emissions. Conversely, considering structural changes in our CGE model shows Chile advancing towards its declared Nationally Determined Contribution (NDC) to reduce greenhouse gas emissions. Furthermore, the methodology implemented in the study has the advantage of being a simple integrated approach that is coherent with current modeling capacities in many developing contexts.

1. Introduction

A heavy dependence on external fossil fuel sources and a rapid increase in energy demand have resulted in high environmental and ecological cost threatening Chile's long-term sustainability. Over the past two decades, energy-related CO2 emissions quadrupled reaching 80 MtCO2 in 2015 (IEA, 2018). The power sector is a principal source in generating harmful emissions to the environment accounting for 40% of total CO2 emission in 2015 (IEA, 2018). The latest estimations by the International Energy Agency (IEA, 2018) and Chile's Ministry of Energy (2018) project that energy demand will grow even stronger, more than doubling by 2050 under the Business as Usual (BAU) scenario. Therefore, an expected high level of growth in electricity demand remains a principal concern for coming years in Chile, requiring significant investments in generation capacity and energy infrastructure. This expansion of the power sector will imply significantly higher CO2 baseline emissions in the near future, and consequently the need for significant mitigation efforts to reach CO2 emission targets.

However, over the last few years, the Chilean power sector has experienced an important transition to Non-Conventional Renewable Energy (NCRE)[1] sources. The energy generation from NCRE has grown extraordinarily fast, surpassing earlier predictions and becoming one of the largest renewable energy markets in South America. Five years ago, the share of the NCRE in the total installed energy capacity accounted for only 5%. This percentage has more than quadrupled in the last few years, reaching 22% in September of 2019. Considering large hydropower plants over 20 MW, the share of total renewable energy sources in the Chilean energy mix accounts for around 50% (CNE, 2018). Among the different technologies, solar PV and wind energy present the largest share of NCRE in

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[1] RES includes non-conventional energy: solar, wind, biomass and small hydro energies, excluding large hydro.

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the country. As of September 2019, NCRE projects with environmental approval reached 33.5 GW, which is even higher than the total current installed capacity of 25 GW (CNE, 2018). With these changes in the Chilean energy mix, there is a growing need to quantify the economy-wide impacts of alternative renewable energy generation expansions. Of particular interest is the potential impact of this trend on the country's CO2 emission baselines and its efforts to comply with its Nationally Determined Contributions (NDC) according to the Paris commitments. These recent and projected changes have made it necessary to quantify the economy-wide impacts of alternative renewably energy generation expansions in the Chilean energy mix.

Many studies have been conducted using power-sector modeling to evaluate both energy and environmental policies (Yu et al. (2018); Liu et al. (2018)) These studies can be mainly categorized into two groups: those that focus on the top-down Computable General Equilibrium (CGE) models and those that use bottom-up-based simulation and optimization engineering models. CGE is a macroeconomic approach which represents economic-wide interactions among the various economic agents providing feedback on prices, commodity and factor substitution, income, and economic welfare (Nong (2019); Lise (2006); Zhu et al. (2019)).

These CGE-based models allow macroeconomic, sectoral distribution and environmental impacts associated with specific shocks and policies to be obtained. The energy sector in conventional top-down models is typically presented at the relatively aggregate level of production functions. Therefore, specific power generating technologies are not identified or detailed. In most cases, the power sector is not disaggregated, but rather it is treated as a single sector with capital, labor, fuel and other inputs for production (Sue Wing, I. 2006). This is a major weakness when assessing the impact of different energy baselines, since structural changes, such as those observed in Chile with the entrance of various emerging technologies, cannot be adequately incorporated in the traditional CGE modeling process. A second, related concern is that the degree of substitution between power generation technologies – in particular new sources – is captured in simple production functions through constant elasticities of substitution (CES) (Aguiar et al., 2016; Paltsev et al., 2005). As a consequence, more generic and energy restrictive top-down CGE models can create doubts for policymakers about the usefulness of CGE-based energy and environmental policy simulations.

In contrast to top-down CGE models, bottom-up-based simulation and optimization models are more popular within energy analysis and planning fields (Taylor et al., 2014; Yang et al., 2017; Chen, 2005). These models include detailed analyses of energy technologies with both technical and economic parameters. Therefore, resources, technologies and users can easily be modeled with the desired scope and detail. However, the bottom-up approach fails to provide feedback on the rest of the economy including possible reallocation of resources, economic growth, sectoral impacts and social effects.

Coupling bottom-up engineering models and CGE models allows more realistic technology-based scenarios to be examined when using the economy-wide CGE models. However, this has not been done systematically in developing contexts where modeling capacities and available data are relatively weak. To fill such a research gap, this study aims to present a simple, first-step approach in the coupling that allows different energy scenarios from a bottom-up engineering model to be incorporated into the CGE model to determine an emission baseline that is more in line with expected structural changes in the generation sector. During the last two decades, CGE experts have explored ways to integrate bottom-up engineering details of energy technologies into the usual top-down CGE macroeconomic representations (Kumbaroglu and Madlener, 2003). In the literature, the most commonly used approaches to link top-down CGE and engineering-model types are classified as soft-linking versus hard-linking (Wene, 1996). However, use of these terms is not consistent in the literature. The soft-linking approach is usually applied when information transfer between the models is directly controlled by the user, whereas the hard-linking approach is typically referred to as a hybrid or a mixed complementarity problem in which information integration is carried out without any user control – usually by computer programs (Krook-Riekkola et al., 2017). In hard-linking, related characteristics of top-down CGE and bottom-up models are highly integrated into one model and solved simultaneously.

Although linking a CGE model and an engineering model have been tested in the context of various countries, mostly developed ones (Hasegawa et al., 2016; Messner and Strubegger, 1995; Murphy et al., 2007), no studies have been found about Chile and the South American region using such a methodology. With the purpose of assessing different energy options in an energy source portfolio and policy implications, some international scholars in South America have been studying the common traditional approaches, either bottom-up applied to energy planning or top-down applied to economic-wide problems (O'Ryan et al., 2003). We acknowledge that full integration or linking is not possible for Chile at the current stage of modeling due to the inherent difficulties of developing such a model and maintaining it over time. For this reason, a first contribution of this work is to describe a simple one-sided linking approach to determine possible emission baselines for Chile. Our approach requires neither a deep expertise in bottom-up engineering modeling nor a convergence of both models. From this starting point, we hope to see others incorporate this process towards creating a more sophisticated and integrated modeling approach for Chile and other countries in South America.

A second contribution of this study is to examine the economy-wide effects of the renewable energy expansion scenarios on the Chilean economy, particularly, on CO2 emission baselines. Specifically, we examine the differences between the coupled and uncoupled CGE model under different energy scenarios. The discussion of the topic is certainly an important issue not only in Chile but at the global level given that most nations are now striving to increase their share of renewable energies in their energy generation mixes. While a limited number of similar policy analyses have been found in this respect in the context of various countries (Willenbockel, 2017; Böhringer and Rutherford, 2013) no related studies have been done about Chile. Most studies have either focused on examining the economy-wide impact of individual electricity generation technology (e.g. CSP, solar PV) (del Sol and Sauma, 2013) or have been specific to the performance of the overall power supply system, usually by examining the impact of renewable generation in the Chilean power system (Urzúa et al., 2016).

The research questions that follow will be answered in this study. Considering modeling capacities in a developing context, is it possible to improve the CGE CO2 emission baseline, incorporating expected generation technologies in a simplified way? How do projected economic, social and environmental impacts change when bottom-up scenarios are linked to the CGE model for Chile? To answer these questions, this paper is organized in six sections. As a continuation of this section, Section 2 describes Chilean energy policy and its relation with CO2 emissions in particular. Section 3 details the one-sided linking approach used. Next, results for three baseline scenarios of renewable energy expansions between 2013 and 2030 for Chile are described in Section 4. The discussion in Section 5 is focused on how the approach used can improve medium-term baseline projections, and Section 6 presents the main conclusions and suggests the policy implications of the proposed approach.

2. Chilean energy policy, its relation with CO2 emissions

Historically, Chile has been largely energy self-sufficient providing most of its energy needs from local and clean hydro energy sources located in the south of the country. In the 1980s, hydro-power resources accounted for more than 70% of the total electric system installed capacity in Chile. However, starting from the mid-1990s with the arrival of Argentine gas, this tendency has deteriorated significantly to transform the country into one of the most vulnerable countries in terms of energy concerns in South America (Nasirov and Silva, 2014). Environmental and social concerns regarding large hydro-project developments, the unreliability of hydropower due to recurring drought periods, and a lack of a long-term energy diversification policy have dragged the power sector into a critical situation in terms of meeting the country's growing energy needs. Consequently, over the last decades, the dependency of the power sector on external fossil sources, mostly in the form of natural gas, coal and diesel, increased significantly reaching 70–80% in the early 2000s (Nasirov et al., 2018).

Furthermore, the combination of scarcity of domestic fossil fuel resources, lack of long-term energy policy, and the intermittency of hydropower made the Chilean economy vulnerable to external shocks. High energy-prices originating from dependence on external energy sources caused substantial impacts on economic activity (Bustos-Salvagno and Fuentes, 2017). The impacts were especially significant in the largest industry sector of the country, the mining industry, which constitutes 20% of GDP and 60% of exports in the country, and where energy has an important share in the total cost of production (Agostini et al., 2017). Today, the Chilean mining industry faces one of the highest energy costs in the world with 12.1 c/kWh, which places it at a disadvantage with respect to its competitors.

As a response to problems of adequate generation in the power system, Chile has adopted several supplementary mechanisms to stimulate the entrance of new investments in the sector. In 2005, Chile implemented a competitive nondiscriminatory auction mechanism aiming to provide transparent prices in the market, to reduce uncertainty for investors, and to foster competition among new entrants and existing suppliers (Nasirov et al., 2018). More recently, in 2014, important changes were introduced in the auction mechanism to make it more competitive. For the first time, Chile established time blocks in the bidding process favoring renewable generators since they can now bid their energy during the times of day when they are producing energy and are not forced to bid for standard 24-h blocks. With this new power auction system, in Chile's latest and also largest energy auction ever, wind and solar photovoltaic (PV) projects constituted around 40% of the total energy auctioned. This increase of NCRE presents a major structural change in the sector.

A lack of long-term sustainable energy policy has resulted in serious consequences in terms of carbon emissions in Chile. Chile's greenhouse gas (GHG) emissions — excluding land use, land-use change, and forestry — are some of the largest among OECD member countries (OECD, 2016) and grew by 113% from 1990 to 2013. Energy-related CO2 accounted for 77% of total GHG emissions and the remaining 23% was provided by methane (CH4) and nitrous oxide (N2O). Over the past two decades energy-related CO2 emissions quadrupled reaching 80 MtCO2 in 2015.

Power generation has become the principal driver in the fast rise of CO2 emissions in Chile between 1973 and 2015 years (See Fig. 1). The role of power generation in CO2 emissions has increased significantly in Chile as the share of carbon-intensive fuels in the energy mix grew rapidly, replacing natural gas and hydro resources in the second half of the 2000s (Nasirov et al., 2018). This rise in carbon-intensive fuels occurred as Argentina closed the pipeline for natural gas to Chile at the same time as hydropower's presence in the energy mix was sharply reduced by droughts and public rejection of this option. In response, coal consumption in electricity generation increased almost fourfold from 1.7 Mtoe in 2005 to 6.6 Mtoe in 2015 (OECD, 2016). In the same period, the carbon intensity of Chile's economy per gross domestic product (GDP) using purchasing power parity (PPP) reached 1.02 tCO2e/million CLP$ 2011.

At the same time, the Chilean government has increasingly recognized the importance of tackling climate change. It has actively participated in international efforts and made commitments to reduce GHG emissions over the past years. Chile signed the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 and ratified Kyoto Protocol in 2002. At the UNFCCC Conference of Parties 15 in Copenhagen in 2009, the Chilean Government voluntarily pledged to reduce emissions by 20% from 2007 levels (the "Business as Usual (BAU)" emissions growth trajectory) by 2020. More recently, in 2016, Chile signed the Paris Agreement taking more serious commitments to reduce GHG emissions on the long-term horizon (O'Ryan et al., 2018). Chile's NDC includes two emissions' mitigation targets for 2030. First, it committed to unconditionally achieve a 30% reduction of GHG emissions-intensity of GDP compared to 2007 by 2030 to reach a value of 0.71 tCO2e/million CLP$ 2011 (subject to economic growth). Second, a further NDC proposal was to reduce GHG emissions-intensity of GDP by 35%–45% in comparison with the levels in 2007 by 2030, conditional on international financial contributions in the form of grants. However, Chile has not defined the responsibilities or the specific instruments to reach these goals.[2]

Over the last decades, an important achievement of the Chilean government has been to develop a mid- and long-term energy strategy. In particular, the National Energy Strategy 2012–2030 and the National Energy Policy 2050 established concrete energy, environmental, and economic goals as essential components of its sustainable development. The National Energy Policy 2050 set main objectives to increase the share of renewable energy in power generation to 60% by 2035 and to 70% by 2050, while also promoting energy efficiency and consumption management. In addition, a new long-term energy planning process (PELP, in Spanish) was recently introduced by the Ministry of Energy in 2017 (Ministry of Energy, 2018). It considers a 30-year planning horizon for generation expansion that will be the basis for inputs from the bottom-up engineering model combined with the CGE model used in this research. According to planning (PELP) estimates, renewable energy sources in the energy mix could represent between 50% and 70% of the new installed capacity, depending on conservative or optimistic scenarios.

3. Methodology

In this paper we undertake a simplified link between the ECOGEM-Chile CGE model and a bottom-up type energy model built by the Chilean Energy Ministry (2018) enabling us to take advantage of the strengths of both models, while at the same time complementing each for its shortcomings. This approach can be

[2] The National Action Plan for Climate Change 2017–2022 (PANCC) is more an administrative document than a specific policy guideline. Another mitigation measure by the Chilean government was to approve the first carbon tax in South America, which took effect in 2018. These taxes target large factories and the electricity sector, which aims to cover about 55% of the nation's carbon emissions. However, the tax level was fixed at USD 5/tCO2; a level deemed too low to have any real impact.

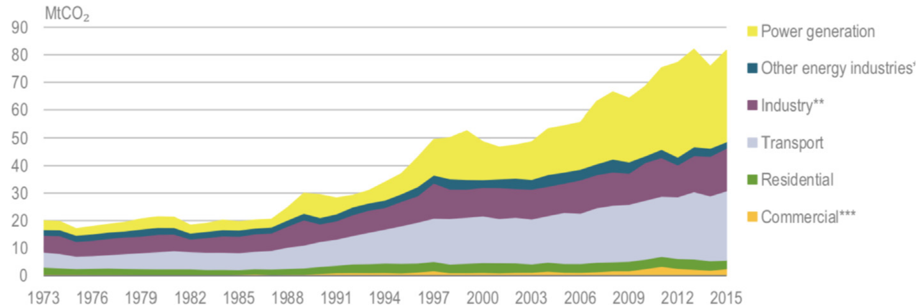

Fig. 1. Energy-related CO2 emissions by sector, 1973–2015.
Sources: IEA, 2018.

defined as a one-sided linking since the bottom-up engineering model has not benefited from the inputs of the CGE model. The advantage of one-sided linking is that it reduces the complexity of complete-linking approaches, while benefiting from the key insights of each model. The specific inputs used in the ECOGEM-Chile are GDP growth and energy mix shares, adopted from the bottom-up model. Outputs of the CGE model included CO2 emissions, GDP, electricity prices and sectorial impacts. Fig. 2 shows how the ECOGEM-Chile CGE model and a bottom-up type energy model are linked. Below we include a brief description of the Chilean CGE model (ECOGEM-Chile) and present its database. Next, we provide an overview of the simulation scenarios from bottom-up modeling and describe how to incorporate bottom-up detailed results into a top-down model.

3.1. Description of the Chilean CGE model: ECOGEM-Chile

The CGE model utilized in this study is a multi-sector, recursive-dynamic model based on the static ECOGEM-Chile model adopted from the original version of the OECD GREEN model (O'Ryan et al., 2003). The model is composed of productive sectors or activities, several occupational categories, income groups (quintiles) for households, public spending categories, final demand spending, trade partners and different pollution types. The summary of the ECOGEM-Chile model in its current status is presented in the Table 1.

In line with an important feature of the neoclassical model, optimization behavior in the production sector is based on the cost minimization concept where each sector minimizes its costs for each level of production. In the nested input/factors tree, the Leontief and the CES/CET (i.e. constant elasticity of substitution – transformation) type functions are employed. The nested production tree includes various levels. In the tree's first level, a CES function is used to choose between a non-energy-producing intermediate input basket and a basket of factors (i.e. capital and labor) - energy producing inputs (KEL). Since there is no substitution between the inputs in the non-energy-producing intermediate input basket, a Leontief-type function is assumed. On the factor side, the capital-energy basket is separated from labor using a CES function, and then energy and capital are split through a new CES function.

Since this model will be used to determine future emission baselines, the electric power sector has been restructured to include renewable sources. This is the first important change required to start the linking process with engineering models that present detailed projections of these energy sectors. The new, nested structure will be discussed in more detail in section 4.4.

Households use their income for consumption and savings. Household decisions are modeled by an ELES utility function (Extended Linear Expenditure System). Each household maximizes ELES utility subject to its budget constraints. This function also includes a minimum subsistence consumption level, which is

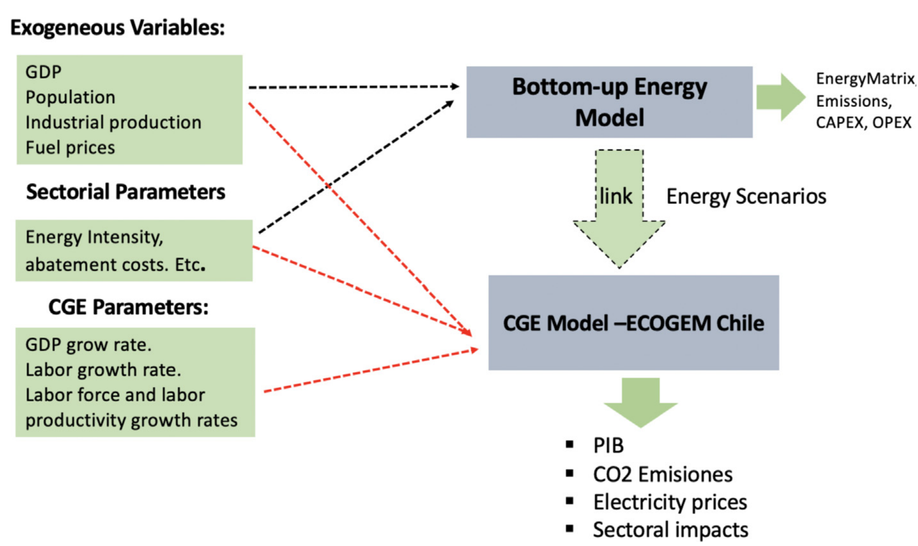

Fig. 2. Linking scheme of the ECOGEM-Chile/CGE and a bottom-up engineering model.
Sources: Own elaboration.

Table 1
Summary of Characteristics of the ECOGEM model.

Characteristics	Description
Sectors and activities	61 sectors: 27 productive sectors, 7 energy generation sectors, 27 services (including water, health, transportation among others)
Occupational categories	12 categories: high-, medium- and low-skill disaggregation by gender (Male/Female) and by place (Urban/Rural)
Household income groups	10 deciles: income groups
Trade partners	35 trade partners: Brazil, USA, China and others and groups of countries or regions (rest of Asia or America and others)
Public finances	Breakdown of taxes and transfers: direct and indirect taxes to businesses, direct taxes on households (income), labor tax, tariffs, VAT and government transfers to households from/to abroad
Pollution	6 types of pollutants: Chile's own emission factors have been estimated by sectoral production and final consumption for airborne pollutants.

independent of the level of income. The final demand is composed of intermediate demands, household demands and the rest, which include investment, government consumption, and trade margins. These intermediate demands are modeled through fixed shares of the total final demand.

In considering the business relations with trade partners, imports and exports are modeled. Consequently, the commodities are differentiated with respect to their destination (sales to the domestic markets or exports) and to their origin (domestically produced commodities or imports). The domestically produced commodity is sold either in the domestic market or the foreign market. The transformation of domestic production is modeled according to the Constant Elasticity of Transformation (CET). On the other hand, the domestic demand originates from domestic and foreign sources. The commonly used Armington assumption is adopted to break down demanded goods by place of origin, and then composite good is determined. This composite good is either used as an input into the production process of domestically produced commodities or sold for final demand including private consumption, government consumption and investment. In addition, in order to allow the existence of multiple business partners, the model includes two nested CES levels to represent the Armington specification. At the first level, agents choose the optimal combination between national goods and an imported good. At the second level of nesting, agents choose the origin from which they import goods as a function of prices and degree of substitution between regions. This second level also uses a CES aggregation function.

In order to achieve equilibrium in the labor market, labor supply and demand are made equal for each occupational category. As for the capital market, it is assumed that there is only one type of capital, which can be more or less mobile among the productive sectors. The mobility of capital between sectors is adjusted based on the specific elasticities, which may use a zero elasticity for the "short-term" scenario and a high elasticity for a greater mobility to characterize "medium-term and long-term" conditions. The model considers three macroeconomic closures that must always be met: the closure condition for public finances, the external closure (current account of the balance of payments, which includes the equilibrium of the trade balance) and the saving and the investment equality. Finally, the model allows two options for the numeraire. The first is the GDP deflator, which is the reference price for the economy. The second option is the exchange rate.

Finally, the model used here is a recursive-dynamic model based on the static ECOGEM-Chile model, which solves for several periods and connects them through the capital accumulation. Capital is allocated among sectors using the relative rates of return. In the model, GDP growth and depreciation rates, population growth and labor productivity are exogenous. The key dynamic parameters adopted in this research are the following: i) an average of 3.2% GDP yearly growth rate is adopted between years 2018 and 2030; ii) population grows at 0.88% in 2014 and growth decreases steadily until 2030 (0.47%); iii) the labor force and labor productivity growth rates are assumed to be 1.7% and 1.0% respectively over the period; iv) net foreign savings as a share of GDP are effective values up to 2017 and held constant at 1.5% of GDP from 2018 on; v) stocks are reduced by 50% in each period.

3.2. Description of the database

A CGE model's database has two important components. The first is the Social Accounting Matrix (SAM), which describes the circular flow of income and spending in a national economy for a specific time period. The second component of the CGE model database presents elasticity parameters, which measure behavioral responses. The latest SAM for Chile was constructed based on the 2013 input-output matrix provided by the Central Bank of Chile (Central Bank, 2013). As the first step in the construction of the SAM, a Macro SAM was developed that includes Commodities, Activities, Labor Factor, Capital Factor, Firms, Households, Government, VAT, production taxes and other taxes, Tariffs, Capital Account, Stock Flow, Margin and the Rest of World (RoW). Following the top-down approach method proposed by Thorbecke (2001), the Macro SAM is disaggregated using secondary statistical sources. The resulting SAM has 55 sectors, 12 labor categories (rural/urban and male/female), 10 income groups (divided by deciles) and 35 trade partners (see Table 1). An important characteristic of electricity generation is that the original data from the input-output matrix is a single sector (an aggregate of existing renewable and conventional technologies) without disaggregation into different technologies. Data on social variables, labor and consumption as well as foreign trade information were collected from the Central Bank. Other main statistical sources include the Socio-economic Characterization Survey CASEN, National Accounts of the Central Bank, Customs, Survey of Family Budgets as well as data on information from the Annual National Industrial Survey, ENIA.

3.3. Simulation scenarios from bottom-up modeling

The choice of energy scenarios to analyze baseline scenarios in the CGE model is based on the prospective long-term energy planning scenarios built by the Chilean Energy Ministry (2018). These scenarios were constructed in compliance with economic, technical, political and social realities, and the interests of the Chilean energy sector. In other words, each scenario has a high relevancy with the challenges faced by Chilean energy sector. These scenarios were evaluated by the Energy Ministry of Chile quantitatively using the bottom-up model, the energy demand model (econometric simulation base on LEAP), and the electric expansion model PET (Co-optimize Gx+Tx) (Chilean Energy Ministry, 2018). The objective of the optimization algorithm considers the long-term energy planning of 30-year simulations to generate different

Table 2
The simulation scenarios.

Factors	Scenario A	Scenario C	Scenario D
Social aspects for the projects	+Cost and CCS carbon	+Cost and CCS carbon[a]	+Cost[b]
Energy demand	Low	Medium	Low
Technological changes in storage batteries	High	Medium	Medium
Costs of environmental externalities	Current	Current	Current
Investment costs in renewable technologies	Low	Medium	High
Price of fossil fuels	Medium	Low	Low

[a] This considers the cost of the installation of CCS technologies.
[b] It assumes that technologies face a higher investment cost due to delays in construction periods because of a greater opposition to their development.

energy scenarios.

A total of six factors are considered in constructing each scenario (See Table 2). As seen in Table 2, for three of the scenarios the first factor considers social challenges of the electricity generation projects in certain areas of the country, particularly thermal, hydroelectric and wind generation technologies in the south of the country. The second factor is the energy demand. The main long-term determinants of energy demand are air conditioning, electro-mobility, energy efficiency and economic growth. The technological change in storage batteries is the third factor considered in the projections. It mainly considers development and cost of energy storage technologies in storage batteries. The fourth factor is the cost of environmental externalities and considers both local and global externalities. The investment cost of the renewable technologies for generating electricity was considered as the fifth factor. The technologies considered are wind, photovoltaic solar, solar power concentration (CSP), run-of-river hydraulics, biomass and hydraulic pumping stations. The sixth factor is the price of fossil fuels. In this context, the fuels considered were coal, diesel, fuel oil and LNG.

The scenarios describe different paths of development in the power generation sector in Chile, and their implications on the proportions of renewable sources in the energy portfolio. For the purpose of this study, the share of energy generation technologies in variants of the scenarios is calculated (See Table 3). As seen in Table 3, the share of non-conventional renewable energy technologies (solar, wind and biomass) in the energy generation mix under Scenario A accounted for 17.8% by 2030. However, this scenario considers the development of large hydro resources in the south of the country if current opposition to such projects weakens. In the context of large hydro developments, the share of these resources in the energy mix reaches 40.1% by 2030 showing a significant growth from its current level. From the environmental point of view, in scenario A, the energy matrix is constituted by a total of approximately 60% clean energy resources in 2030. On the contrary, the role of coal sources increases from 30% in 2025 to 39% in 2030. In Scenario C, there is a significant growth in solar and wind energy sources over time. The share of these technologies in the energy generation mix reaches 30% by 2030. In addition, electricity generation through LNG increases reaching its highest level of 6.4% in 2030. The electricity generation from coal and large hydro sources decreases slightly in 2030 compared to 2025. In contrast to the previous scenarios, coal-based electricity generation weighs heavily in Scenario D, and at the same time an increase in LNG generation is observed.

3.4. Incorporating bottom-up results in CGE modeling

3.4.1. Improvement to the database

As a first step in relating a bottom-up model to a CGE model, it is necessary that the SAM include a more detailed decomposition of the electricity generation sector, currently aggregated into one sector. Following the methodology proposed by Su Wing (2006), the top-down macroeconomic representation of the sector is disaggregated into seven power technologies: coal, diesel, gas-fired power, hydro, wind, biomass and solar PV. The main sources of data used in the disaggregation were provided by the National Energy Commission and the National Energy Balance. The disaggregation in the study was realized based on the representation of the power generation sector in the six submatrices of the SAM. These include production, intermediate consumption (national and imported), tax payments, wage incomes, gross operating surplus, and household consumption (own generation). As a result, the modified 2013 SAM considers 61 sectors.

Table 3
The shares of the generation technologies per scenario for 2025 and 2030 years.

	Scenario A		Scenario C		Scenario D	
	2025	2030	2025	2030	2025	2030
Solar[a]	6.3%	8.3%	8.7%	14.1%	8.8%	10.8%
Biomass	3.8%	5.0%	4.0%	3.7%	4.0%	3.9%
Wind	3.4%	4.5%	12.5%	11.1%	12.7%	11.8%
Coal	29.6%	38.7%	37.2%	33.3%	37.2%	35.7%
Nat. Gas	1.7%	2.2%	2.6%	6.4%	1.7%	4.5%
Diesel	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Hydro[b]	30.7%	40.1%	34.0%	30.5%	34.6%	32.5%

[a] Includes Solar PV and CSP.
[b] Includes large and small Hydro.
Sources: Own Elaboration based on data adapted from Energy Ministry of Chile, 2019.

3.4.2. Improvement to the CGE model

To incorporate bottom-up results, two changes were required in the CGE model. First, the electricity generation sector had to be moved from the intermediate input branch to the KEL branch, allowing for a substitution between electricity and other energy sources. A second important modification[3] was decomposing the electricity generation sector into conventional (solar and wind) and non-conventional (hydroelectric, biomass, coal, natural gas and diesel) generation sources, the main sources identified in Fig. 3. This allows for substitution among these sources or imposing specific shares of each.

After improvements to the database and the CGE model, it was possible to replicate the external information from the electricity generation scenarios A, C and E and incorporate the structural changes expected in the electric power sector. To achieve this linking, the energy mix (the share of different energy technologies) for each scenario from the bottom-up approach is incorporated in the CGE model by requiring that the share of each energy source be the same each year. For this purpose, the production function in the ECOGEM considers that the elasticities of substitution between the

[3] We follow the EPPA (20xx) decomposition here.

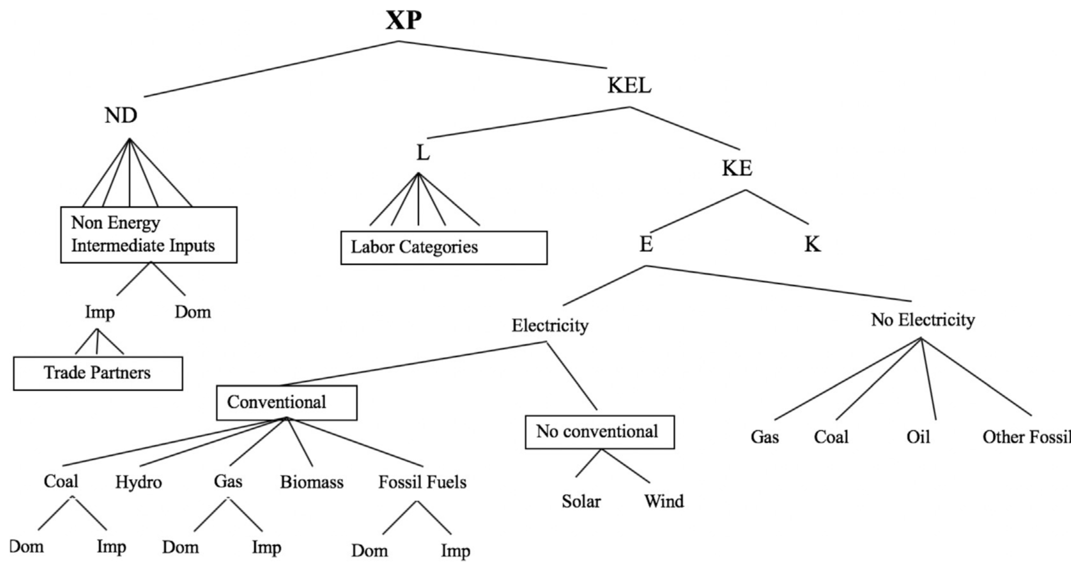

Fig. 3. The productive structure of the modified CGE model.
Sources: Own elaboration.

different energy products in each sector are set to zero ($\sigma = 0$), i.e. the energy branch is assumed to be represented by a so-called Leontief structure (with fixed-input coefficients). Using external energy scenario projections, the electricity generation demand by technology can be varied per year. The percentage growth of the shares in the electric generation of each technology for each of the three scenarios is used as a parameter to increase or reduce the requirement of intermediate goods and value added plus energy from each technology as presented in Table 4.

Where XP is the amount of electricity produced by the generation activity (technology-tec).$\mathbf{ND}_{tec,t}$ and $\mathbf{KEL}_{tec,t}$ is the demand for technology that makes intermediate consumption and value added plus energy, respectively. The percentage growth of the share in the electrical generation of each technology in each scenario is $\Delta\mathbf{gen}^{\mathbf{esc}}_{\mathbf{tec}}$. Furthermore, $\mathbf{andx}^{\mathbf{bau}}_{tec,t}$ and $\mathbf{akel}^{\mathbf{bau}}_{tec,t}$ are the Leontief coefficients or coefficients of proportion "fixed" for intermediate consumption and value added plus energy.

4. Results

This section describes the simulation results for four baseline scenarios of renewable energy expansions between 2013 and 2030. First, a BAU baseline scenario based on the original database and no coupling is used. Scenarios A, C and D represent the results including expected structural changes in the Chilean energy portfolio. For these scenarios, the inputs of a bottom-up engineering model are employed in the CGE model. The results are described for CO2 emissions, CO2 emission intensity pathways, and the economy-wide impacts of the three renewable energy portfolio scenarios.

4.1. Results on CO2 emissions and CO2 emission intensity

Fig. 4 describes the baseline scenarios for CO2 emission pathways between 2013 and 2030. Under scenarios A, C and D, total CO2 emissions increase by 47%, 48% and 52% respectively. Compared to the BAU scenario, CO2 emissions are 10–15% less. This is because the share of RES in the energy portfolio is significant under scenarios A, C and D. Additionally, the sharp decreases in CO2 emission pathways observed in scenarios A and C in 2018 and scenario D in 2020 can be explained by the fact that in these specific years, clean hydro resources were integrated in the energy matrix.

Fig. 5 presents the results of the simulation on CO2 emission intensity pathways between 2013 and 2030. As seen in Fig. 5, the results show reductions in all scenarios. However, compared to scenarios A, C and D, CO2 Emission Intensity under the BAU decreases slightly (between 1 and 2%) and gradually for the first period of the simulation, then becomes rather stagnant over the next decade. However, the simulation results show that this situation can be improved under scenarios A, C and D. Therefore, as seen in Fig. 5, emission intensity under Scenario A, Scenario C and Scenario D could be reduced by 12% on average compared to the BAU scenario. This is mainly because the weight of clean energy sources in the actual 2018 structure of primary energy consumption is increasing significantly.

4.2. Results on economy-wide impacts

Fig. 6 describes the impact of different energy portfolios on GDP for the period of 2013–2030. As seen in Fig. 6, GDP rises around 70% under all scenarios between 2013 and 2030. However, there is a slightly higher increase in GDP in Scenarios A, C and D relative to

Table 4
Substitution in the use of energy inputs for electricity generation by type of technology.

Parameter of energy demand (base scenario or BAU)	$\mathbf{andx}^{\mathbf{bau}}_{tec,t} = \frac{\mathbf{ND}_{tec,t}}{\mathbf{XP}_{tec,t}}\mathbf{akel}^{\mathbf{bau}}_{tec,t} = \frac{\mathbf{KEL}_{tec,t}}{\mathbf{XP}_{tec,t}}$
New parameter of energy demand (energy scenario)	

Sources: Own elaboration.

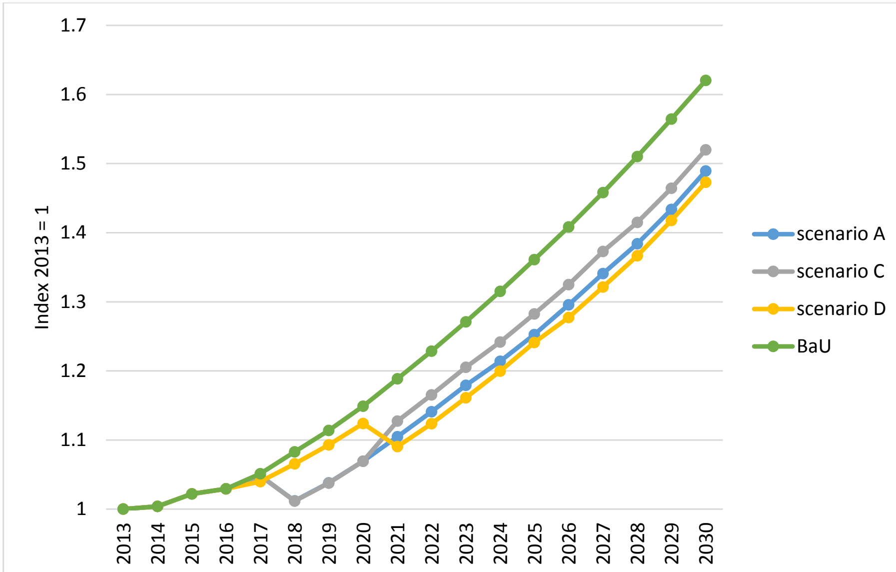

Fig. 4. CO2 Emissions per scenario.
Sources: Own elaboration.

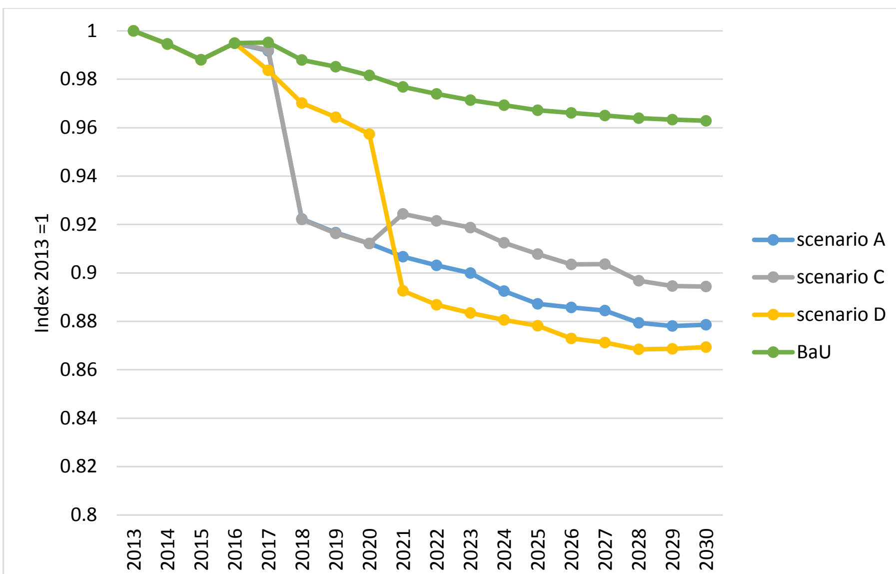

Fig. 5. Emissions intensity per scenario.
Sources: Own elaboration.

the BAU scenario. This is due to the entrance of renewable energy sources at a lower cost in these latter scenarios.

The results of simulations show that structural changes with the entrance of renewable energy sources in the Chilean power market firstly impact the power industry itself. The effect of the different scenarios on power prices is described in Fig. 6. All scenarios show a steady decrease in electricity prices between 2013 and 2030. However, there are significant differences between the BAU scenario and Scenario A, C, D. This difference is even larger between the BAU scenario and Scenario C reaching about 11% in 2030. This can be explained by a massive increase of renewable energy resources at a zero-marginal cost in the Chilean power system in the future.

In addition, the percentage changes in sectoral outputs are quite significant for the electricity related industries (see Table 5). The transmission and distribution sectors under one-sided linking scenarios (Scenario A, C and D) record significant positive percentage changes from the BAU scenario. This amounts to an average of 10% and 12% respectively in 2030. It is also evident from the simulation results that the primary energy sources for the thermal electricity technologies will suffer the most under expansion of renewable energy sources. Currently, thermal electricity technologies rely mostly on natural gas, oil and coal as an input in the production process (see Table 5). As seen in Table 5, the results in the context of oil, natural gas and coal sectors indicate large percentage decreases from the BAU scenario in 2030. Coal records the largest negative growth by 9.6%, 8.7% and 10.6% under Scenario A, C and D respectively in 2030. The chief output gainer is RE electricity

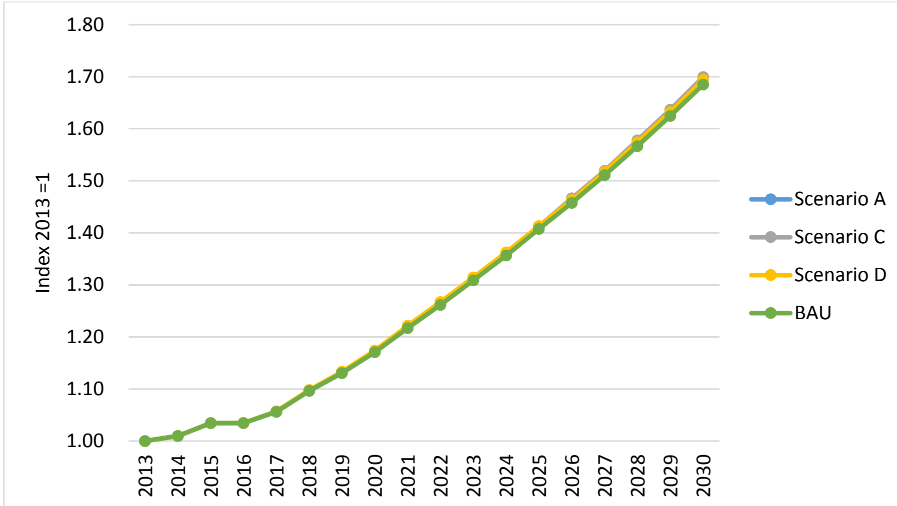

Fig. 6. GDP growth between 2013 and 2030.
Source: Own elaboration.

Table 5
Production changes in electricity-related sectors: percentage change from the BAU scenario.

Variables	Scenario A	Scenario C	Scenario D
Transmission	9.8%	10.0%	10.1%
Distribution	11.4%	13.6%	11.1%
Thermal Energy			
Oil	−1.1%	−1.6%	−1.0%
Natural gas	−4.0%	−3.4%	−4.4%
Coal	−9.6%	−8.7%	−10.6%
Clean energy technologies	109.8%	114.5%	113.5%

Sources: Own elaboration.

at 109.8%, 114.5% and 113.5% in Scenarios A, C and D respectively in 2030.

Table 6 describes production variations under different scenarios from the BAU scenario in 2030 for other main industrial sectors. As shown in Table 6, the scenarios examined in the study do not generate large variations from BAU in the domestic economy as the main sectors of the Chilean economy are not greatly impacted. However, there are some winners. Among the scenarios, all sectors have progressed better under Scenario C. This can be explained by the fact that energy prices are much lower in Scenario C as observed in Fig. 7. As seen in Table 6, the mining sector loses slightly. This could be the result of the increasing cost of qualified labor.

5. Discussion

The results obtained show that it is possible to improve medium-term baseline projections from a country level CGE model using a simple one-sided coupling approach, without the need to significantly change the original CGE model. Improvement in this case means that the model can replicate the structural change expected in the electricity generation sector due to the incorporation of renewable sources. In developing contexts where modeling efforts are usually discontinuous and underfunded, such an approach can be useful to generate more credible results.

Table 6
Production Changes for Main Industrial Sectors in Chile: Percentage change from BAU.

Variables	Scenario A	Scenario C	Scenario D
Agriculture	0.2%	0.3%	0.2%
Mining Industry	−0.3%	0.0%	−0.4%
Fishery Industry	0.1%	0.2%	0.1%
Water Sector	0.4%	0.5%	0.4%
Construction	0.2%	0.3%	0.2%
Forestry	1.5%	1.9%	1.4%

Source: Own Elaboration.

5.1. Analysis of the differences between the scenario BAU and scenarios A, C and D

When using a traditional CGE model, the data representing the economic structure of the country – the Social Accounting Matrix – is compiled with data from several years in the past. For example, in Chile's case, the most recent integrated data dates from 2013, now six years in the past. The structural changes expected in the future, led by shifting consumer preferences, demographic changes, emergence of new technologies, replacements in the endowments of primary resources (including human capital), etc. (Britz and Roson, 2018) are not captured, such that past realities continue to be reflected when using traditional CGE models even though those realities are no longer relevant to the present or future. This is particularly observable in this research because the Chilean power sector has experienced significant changes with the entrance of massive renewable energy resources over the last few years, changes that will become deeper in the next decade. In this context, using the 2013 database to project the future through a BAU baseline scenario gives a misleading picture.

The results of this study show that incorporating different energy portfolio scenarios from a bottom-up engineering model in the CGE model through a simple linking approach could be an initial way to overcome this problem, without having to start again to create a fully-updated and more complex CGE model. The results obtained under the original CGE BAU baseline scenario in the study are significantly different from bottom-up based scenarios A, C and D that include emergent generation technologies. In the BAU, Chile's energy generation mix is still mainly made of fossil fuel sources (gas, carbon and diesel) accounting for about 65% of total energy generation, whereas in the alternative scenarios it drops to less than 40%.

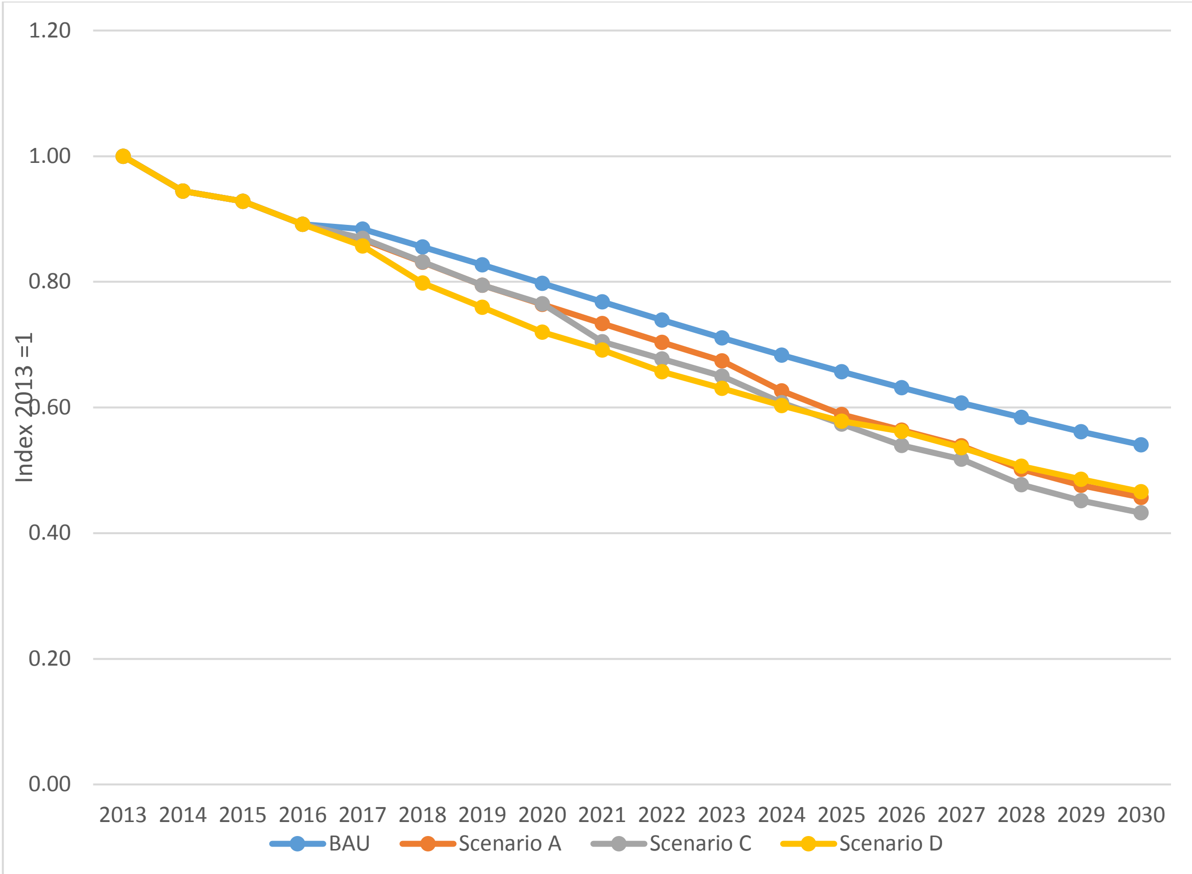

Fig. 7. The change of electricity prices between 2013 and 2030.
Source: Own elaboration.

5.2. Analysis of the impact of renewable energy expansions in the Chilean energy mix

The changes in the energy matrix have impacts on CGE model baseline emissions and on the structure of the economy. The results show that the expected transition from fossil fuels to low-carbon renewable technologies will play an essential role in reduction of CO2 emissions but will fall short of Chile's emission intensity NDC for 2030. In fact, the alternative scenarios with significant incorporation of renewables still increases total emissions by close to 50% in 2030. This is mainly because the energy matrix under all simulated scenarios still largely relies on carbon plants, which are important drivers of CO2 emissions. Currently, the Chilean power system has 28 active coal-fired power plants, averaging 18 years in operation and providing almost 40% of the country's power, while generating 26% of all greenhouse gases. De-carbonization of the power sector by retiring coal-fired power plants and replacing them with renewable energies would generate better results.

From an economy-wide perspective, electricity prices will decrease steadily between 2013 and 2030 under the different renewable expansion scenarios, stimulating a slight growth in GDP relative to the BAU baseline. Two major factors determine this reduction in electricity prices in the Chilean decentralized power system, the capital cost and the generation cost of energy technology. Technological advances have been crucial in the deployment of solar PV and wind technologies in Chile, making them more cost-competitive. In the case of solar PV, solar panel prices have fallen from US$ 4.15/W in 1996 to US$ 0.37/W in 2017 (REN21,2018). The annual levelized cost of solar energy technologies, particularly utility-scale solar PV, has fallen from over $100/MWh to $40–46/MWh, making it competitive with fossil fuels such as gas and coal in many locations. This trend will continue in the future. The second driving factor is the relative generation cost of renewable technologies, which is zero.

Finally, changes in sectoral outputs are quite significant for the electricity industry. As expected the thermal generation sector and its related sectors will suffer the most while solar and PV sectors increase their production. The transmission and distribution industries show relatively high positive growth largely due to the development of renewable energy projects in remote zones, far away from large energy demand centers. In fact, because of Chile's geographic characteristics, projects are located either in the north of the country in the context of solar energy or in the south for wind and hydro energy sources, all of which are far from large cities.

6. Conclusions and policy implications

Over the past decades, Chile has experienced a significant growth in CO2 emissions as a result of strong reliance on carbon-intensive fuels, mainly coal and diesel plants for electricity generation. However, a massive penetration of NCREs in its energy matrix has resulted in a tenfold increase in installed NCRE capacity since 2013, which is the CGE model base-year currently available for Chile. Additionally, there are many NCRE projects with environmental approval waiting to enter operation. Consequently, almost all new future electrical generation will be based on clean energy sources.

To evaluate the impact of these structural changes, an economy-wide CGE model has been combined with a bottom-up engineering model to better incorporate the relevant changes. This process uses a one-sided linking to simplify the integration process and take advantage of both models. Four different baseline scenarios were constructed and compared in this study. The results show that there are significant differences in CO2 emissions and emission intensities among scenarios. In the context of sectorial changes, the power sector itself has been impacted significantly. When engineering model inputs are incorporated in the CGE model, these indicators are reduced significantly compared to a BAU scenario. The differences in the case of CO2 emissions in the year 2030 range from 10 to 15% and in the case of carbon emission intensities from 7 to 10%.

Nevertheless, the improvements in the emission baseline that result from the modeling approach used here show that expected emissions will still be significantly higher than what is required by the country's NDC commitment. This improved baseline will allow a better assessment of the policy options required to reach the country's goals in terms of CO2 emissions. In particular future CO2 emission taxes, the phasing out of coal power generation, electromobility and improvements in energy efficiency are all expected to play a role in advancing towards our CO2 emission goals. In the longer run there are significant technical challenges that must be addressed to obtain a successful energy transition. Activities such as building regional interconnection systems with the neighboring countries, investing in energy storage technologies, developing demand side management programs and investing in complementary technologies are some of the steps that must be assessed starting from a credible baseline like the one proposed here.

In conclusion, including structural changes in the energy sector combining the modeling efforts from both bottom-up and top-down approaches provides relevant information for more realistic policy analysis in a developing country context, such as Chile. Furthermore, the methodology implemented in the study has the advantage of being a simple integration approach that does not require deep expertise in bottom-up engineering modeling and could be used to create a more sophisticated and integrated modeling approach for Chile and other countries in South America. This type of model may also be applicable to other areas. For example, it could be used to incorporate a different production path for Chile's copper sector due to a decrease in productivity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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