Tradeoffs between economy wide future net zero and net negative economy systems: The case of Chile

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Abstract

Given the possible economic consequences, poorer countries have more challenges in delivering their Nationally Determined Contributions. As a developing country, Chile has pledged to attain carbon neutrality by 2050. While Chile has implemented several mitigation measures, it still relies heavily on carbon sequestration, intending to sequester around 65 $MtCO_2e$ by 2050. However, heavy reliance on sequestration poses several risks as the literature shows that natural sinks, particularly forest and land, are exposed to severe impacts from global warming and climate change. Fortunately, Chile has significant renewable energy potential, which, if fully utilized, may move the country towards a net negative emissions context. To assess if such a net-negative system is feasible in the context of Chile, a new regional version of the Global Change Analysis Model for Chile is developed. The model is used to investigate the effects and required levels of investment in renewable energy and decarbonization of end-use sectors to achieve economy-wide net negative emissions scenarios. The design of net negative pathways follows a statistical approach based on the expected sequestration capacity in 2050 and its corresponding confidence interval. The results are compared to scenarios that are aligned with the objective of carbon neutrality by 2050. The findings show that obtaining net-zero emissions by 2050 is possible, however achieving net negative systems will be dependent on existing sequestration capacity and the application of economic incentives to boost green energy deployment in Chile as well as to push such green energy, in the form of electricity or e-fuels, into hard to decarbonize final demand sectors, such as transport, mining, and industry demand sectors. The results also indicate that after significantly reducing CO_2 emissions from the energy sector (primarily the power sector), the agricultural sector and other urban and industrial sectors still contribute to non-significant levels of CH_4 and N_2O emissions.

Keywords: Climate and energy policies, Electrification, Nationally determined contributions, Carbon neutrality, Energy transition, GCAM

Acronyms

BECCS Bioenergy with Carbon Capture and Storage
CCS Carbon Capture and Storage
CO_2 carbon dioxide
DAC direct air capture
GCAM Global Change Analysis Model
GHG greenhouse gas
IAM Integrated Assessment Model
IMAGE Integrated Model to Assess the Global Environment
LCA Life Cycle Assessment
LEAP Long-range Energy Alternatives Planning System
NDC National Determined Contributions
PELP Long Term Energy Planning

1. Introduction and literature review

In 2020, the atmospheric concentration of carbon dioxide (CO_2) reached 417 parts per million, well beyond the pre-industrial peak of 300 parts per million, according to the National Oceanic and Atmospheric Administration. Commerce, transportation, energy production, and agriculture are all affected by this growth. Furthermore, the scientific world agrees that the global warming phenomena is significantly connected with greenhouse gas (GHG) concentrations in the atmosphere [1, 2, 3]. As a result, various international and domestic accords have been formed in an attempt to curtail and reverse global warming. The most recent is the Paris Agreement, whose objective is to restrict global warming to well below 2°C and make further efforts to limit it to 1.5°C, relative to pre-industrial levels [4].

In the context of reaching the Paris Agreement and other climate goals, Chile has made tremendous progress in expanding its share of renewable energy. According to the International Renewable Energy Agency, Chile's renewable energy capacity increased from 1.2% of total installed capacity in 2010 to more than 20% in 2020, with solar and wind power accounting for the majority of the expansion [5]. Furthermore, Chile is among the world's top countries in terms of solar energy resources, with the Atacama desert being one of the most suitable places for solar energy generation. The Chilean government has also developed renewable energy regulations, such as auctioning renewable energy contracts and setting renewable energy adoption objectives. Despite these accomplishments, Chile continues to rely extensively on fossil fuels, particularly in both, the transportation and industrial sectors [6, 7, 8]. Hence, the Chilean National Determined Contributions (NDC) and climate goals seek to decarbonize the final energy demand sectors, particularly buildings and the transport sector, while switching to a greener power sector driven by increased solar and wind energy, seeking to achieve carbon neutrality by 2050. However, an important point to consider is that Chilean carbon neutrality significantly relies on carbon emissions sequestration from land use biomass and forestry [9].

Biomass is a finite resource subject to environmental and socioeconomic issues, and there are also great uncertainties about how much it can sustainably add to the energy system [10, 11]. Climate change is exacerbating this instability by affecting humidity, increasing the likelihood of wildfires and severe droughts. As a result, biomass crops and global biomass potential will be adversely affected even in low-warming scenarios. Also, large fires have become more frequent over time. For instance, in 2014, an incident came to light in California as a result of climate change [12, 13]. The case of Chile is another example. According to the Corporación Nacional Forestal [14, 15], in the last decade, there were 59,028 wildfires that affected more than one million hectares. Additionally, according to the Ministerio del Medio Ambiente, Chile was hit by a firestorm in 2017 that released 57 million tonnes of CO_2e into the atmosphere [16]. This corresponds to 86% of the country's sequestration capacity [16]. Moreover, the management of planting and reforestation is a complex issue, making biomass supply and forestry sector more unpredictable. Furthermore, recently in February 2024, Chile faced a devastating wildfire in the city of Valparaíso and Viña del Mar, which consumed over 9,000 hectares, becoming the second deadliest wildfire in history, after the wildfire faced by Australia in 2009. All these climate effects and impacts on land and forests puts Chile at a high risk of achieving its NDC goals.

Given the uncertain context due to climate change and global warming, several countries are facing challenges in order to guarantee their compliance with their NDC. As noted above, Chile relies on significant sequestration capacity, roughly 50% of the current emissions, which is projected to reach 65 $MtCO_2$e (sequestration) in 2050 to achieve carbon neutrality. However, in order to guarantee that carbon neutrality is achieved, uncertainty regarding sequestration capacity must be managed. Therefore, this study develops deep-decarbonization pathways for Chile that are likely to result in a net negative economy-wide system by 2050. In other words, we seek to test the hypothesis that uncertainty related to sequestration capacity can be reduced by utilizing deep-decarbonization pathways considering economy-wide GHG limits. Therefore, the uncertainty faced regarding sequestration capacity can be reduced. The research is developed using a new version of the Integrated Assessment Model (IAM) named Global Change Analysis Model (GCAM), specially developed for Chile (GCAM-Chile) which considers Chile as an independent region with high technological resolution in the energy, land, water, and food sectors.

To assess some of the issues mentioned above, particularly related to sequestration, biomass limits, and negative emissions technologies, several studies have utilized IAMs to assess uncertainties arising from renewable sources or bioenergy considering scenarios involving Bioenergy with Carbon Capture and Storage (BECCS) and pure Carbon Capture and Storage (CCS) technologies. For instance, Muratori et al. [17] evaluated results from the 33rd Energy Modeling Forum study, which considered results of over 10 different IAMs. The results show the importance of carbon removal in attaining objectives aligned with limiting global warming to 1.5°C. Nonetheless, they observe that while the earlier deployment of BECCS may occur, sustained and extensive utilization may not follow. This limitation stems from economic competition with alternative carbon-free technologies, particularly within the electricity sector. Additionally, land-use competition, particularly with food production, impacts the availability and cost of biomass feedstock. Similarly, Yamagata et al. [18] assessed the impact of BECCS deployment scenarios on the land systems including land use, water resources, and ecosystem services. Scenarios under evaluation considered annual negative emissions consistent with the Representative Concentration Pathways 2.6 case. They identify that converting food cropland to bio-crop cultivation threatens future food production, irrigation increases bio-crop productivity but doubles the water consumption, and forest land conversion for bio-energy crops without protecting natural forests harms ecosystems and climate regulation. Hence, careful land use planning is essential to avoid negative impacts on food, water, and ecosystem sustainability in BECCS implementation. Indeed, several studies have explored the role and evolution of natural resources and their impact on the modeling assumptions in IAMs. For instance, Tokimatsu et al. [19] proposes a link between the LIME Life Cycle Assessment (LCA) model and IAMs. The proposed model thus provides a comprehensive perspective on various natural resources and their impacts on a lifecycle basis. However, LCA faces large uncertainties regarding the future to support more robust future environmental impact assessments of technologies. In this context, Mendoza Beltran et al. [20] proposed an approach that systematically modifies the background processes in a prospective LCA based on results of the Integrated Model to Assess the Global Environment (IMAGE) integrated assessment model. The findings show that changes in the electricity background can be very important for the environmental impacts of different technologies, such as impacts on electric and internal combustion engine vehicles.

IAMs such as GCAM, have been widely used to study future global and regional decarbonization pathways. For instance, Feijoo et al. [3] employed the GCAM to assess a range of global temperature targets, including a goal of 1.5°C with and without overshoot. Results indicate that BECCS technologies are critical to achieving the temperature targets. Also, Dafnomilis et al. [21] studied, using the IMAGE IAM, global strategies aligning 2030 emission targets with net zero goals to accelerate the transition to a low-carbon economy. By leveraging existing international climate policies, they show that it is possible to reduce the emissions gap to the Paris Agreement's 1.5°C target by around 90% by 2100. Rogelj et al. [22] performed an IAM comparison study to assess pathways that limited radiate forcing in 2100 to 1.9 Wm^{-2}, consistent with a global mean temperature rise of 1.5°C, under different socioeconomic pathways. Six modelling frameworks (IAMs) were considered, including AIM/CGE, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MAgPIE, and WITCH-GLOBIOM. Results indicate that some socioeconomic scenarios are amenable to 1.5°C pathways, particularly those that result in a rapid shift away from traditional fossil-fuel use, with reduced energy use (energy efficiency), and with carbon dioxide removal technologies.

IAMs have also been used to assess decarbonization pathways in regional contexts or at country levels. A regional-focused study on the USA was developed in [23], where the implications of 2050 emissions budgets were explored using the state-level regional version of GCAM (GCAM-USA). Similarly, Zhang & Chen [24] employed the Integrated MARKAL-EFOM System model of China (China TIMES) to quantify the global average temperature under various emissions pathways, carbon peaks, and carbon neutrality scenarios for China. In the context of Latin America, Villamar et al. [25] built the ELENA-MESSAGE model with a focus on Ecuador, in which sustainable policies were assessed within the context of their NDC. Similarly, Khan et al. [26] adapted GCAM for Uruguay, analyzing energy transition paths considering the energy-water-land nexus. Additionally, Delgado et al. [27] applied GCAM to Colombia, evaluating mid-term NDC strategies. Both Colombian [27] and Ecuadorian [25] studies conclude that existing policies fall short of achieving net zero emissions by mid-century. Utilizing GCAM, Santos da Silva et al. [28] investigated the impact of the Paris Agreement derived mitigation policies on the energy-water-food nexus, emphasizing IAM's capacity for integrated analysis across diverse systems. Binsted el al. [29] assessed, using GCAM, the stranded asset implications of the Paris Agreement in Latin America and the Caribbean. They found that Latin American countries would result in a stranding assets cost of \$37–90 billion and new investment of \$1.9–2.6. Note that this study considered a version of GCAM with aggregated regions, where Chile, Peru, Bolivia, Paraguay, and Uruguay are grouped. In the context of Chile, Simsek et al. [30] used the Long-range Energy Alternatives Planning System (LEAP) model to propose alternative energy scenarios aligning with Chilean NDCs. Finally, a multi-model comparison effort and broader view of decarbonization pathways in Latin America can be found in the CLIMACAP-LAMP project [31], which focused on energy and climate change mitigation in Latin America towards 2050 (mid-century).

In the Chilean context, as mentioned earlier, issues related to increased levels of wildfires and agriculture risk due to water availability put even more uncertainty regarding land and biomass-based strategies toward carbon neutrality. The literature has identified that carbon neutrality scenarios in different contexts are possible (see for instance [30, 32]). However, careful assessment of the impact across systems must be addressed. In this context, few studies focusing on Chilean decarbonization pathways with a cross-system view have been identified (e.g., [9, 30, 32]). Arriet et al. [32] use the GCAM-Latin America (GCAM-LAC) model to also propose alternative carbon-neutral scenarios in the Chilean context by 2050, where the analysis focused on the potential of renewable sources. In addition, Benavides et al. [33] evaluated options to achieve carbon neutrality in Chile based on the assessment of the uncertainty of several parameters based on scenario generation. Vulnerabilities of the current Chilean NDC strategy are identified, particularly, under what conditions sectoral transformations are insufficient to achieve net zero emissions. Based on the results, different alternatives are proposed to reduce the likelihood of not achieving carbon neutrality. Similarly, Matamala et al. [9] developed a probabilistic feasibility assessment for carbon neutrality in Chile based on chance constraints. The study particularly focuses on evaluating the risk of increasing dependence on land and biomass-based sequestration (e.g., BECCS) on reaching 2050 emissions targets. Other studies, such as Simsek et al. [30], and Arriet et al. [32] also evaluate sectoral transformation for reaching 2050 emission targets, but without a probabilistic or uncertainty view (deterministic evaluation of scenarios).

Several authors have also studied decarbonization strategies in Chile but with a specific energy sectoral focus (not focusing on land, land use, forestry, agriculture, or other sectors). For instance, Chang et al. [34] focused on energy system transition based on two different scenario designs. The findings show that Chilean carbon neutrality goals can be achieved with a smart energy system approach and that a 100% renewable energy system is feasible. Similarly, Osorio-Aravena et al. [35] analyzed the impact of renewable energy and sector coupling on the pathway towards a sustainable energy system in Chile. Authors find that transitioning to a 100% renewable energy system would be more cost-efficient from 2035 onwards (fully defossilised energy system). Most importantly, it is found that Chile could become a negative GHG emitter by 2035. Furthermore, Osorio-Aravena et al. [36], as a follow-up of [35], analyzed synergies of energy system sectoral coupling alternatives under geographical multi-node scenarios. The authors also found that a 100% renewable energy system under different spatial resolutions can be achieved via various coupling configurations for the power, heat, transport, and desalination sectors. Simsek et al. [30] generate an energy and environmental model using LEAP to forecast energy demand, supply, and emissions for Chile by 2030. The results found that the demand sector showed a major contribution to emissions reductions when compared to transformation sector, indicating that Chile requires appropriate energy efficiency and renewable energy policies for demand side. Amigo et al. [37] focused on the decarbonization and NDC commitments of the power sector alone. A cap-and-trade strategy (rather than carbon taxes) was analyzed to achieve the commitments. They found that decarbonization (coal phase-out) of the power sector and reaching renewable targets of 70-80% can be done with carbon prices of at least 35 USD/tCO_2. Several other studies in the Chilean context, particularly focused on the power sector and hydrogen development, can be found. For instance, Jorquera-Copier et al. [38] where a new capacity expansion planning model for hydrogen–power networks is developed to produce projections towards 2050 Chilean hydrogen export needs. For other similar studies on the Chilean power sector or energy sector, readers are referred to [39, 40, 41, 42].

Based on the literature review presented above, we identify that the current research on Chilean decarbonization and pathways towards its NDC are mostly focused on the assessment of the energy sector and scenario analysis for reaching carbon neutrality under the assumptions that sequestration capacity from forest, land, ocean, and biomass will act as expected. Most of the research discussed above (with a few exceptions, for instance, Matamala et al. [9], and Benavides et al. [33]) do not consider uncertainty regarding sequestration capacity or other important features. To the best of our knowledge, there is a lack of focus on net negative pathways in Chile or Latin America. Therefore, in this research, we propose a scenario development based on statistical sequestration capacity to determine pathways towards deep-decarbonization scenarios that can (statistically) guarantee that at least carbon neutrality will be reached, and in any other case, net negative economy scenarios will be obtained. The pathways towards carbon neutral and net negative systems are built using a new developed version of the Global Change Analysis Model (GCAM) for Chile (GCAM-Chile), with increasing industrial desegregation that allows to account for decarbonization in the mining sector, a critical end-use sector in Chile. Hence, the new GCAM-Chile model allows to perform the analysis capturing emissions across sectors (beyond the energy sector) and to model the intrinsic linkages between energy, land, water and other sectors. Finally, scenarios beyond carbon neutrality based on GHG emissions are modeled taking into account all GHG emissions from their direct sources, unlike most of the research which work under the assumption of CO_2e emissions, without directly mitigating all GHG emissions simultaneously based on decarbonization of sectors via electrification, or usage of hydrogen, among others.

The rest of the paper is structured as follows: Section 2 presents details about GCAM-Chile model as well as the methods used to determine deep-decarbonization pathways beyond carbon neutrality. Section 3 present details about the Chilean energy system and the scenarios to be assessed. Section 4 presents the results. Finally, Section 5 concludes the research.

2. Model Description and Methodology

2.1. The global change analysis model incorporating country-level representation in Chile

This research developed a new country-level representation of the Global Change Analysis Model for Chile (GCAM-Chile) based on GCAM v6.0, following the work by Flores et al. [43]. GCAM-Chile expands previous versions developed by Matamala et al. [9] and Arriet et al. [32] by including further details in end-use sectors, particularly in the industrial sector. Nine detailed industrial sectors are modeled within GCAM-Chile. These include six manufacturing sectors (iron and steel, chemicals, aluminum, cement, fertilizer, and other industries) and three non-manufacturing sectors (construction, mining energy use, and agricultural energy use). In previous versions, GCAM combines energy, economics, land use, water, and climate systems [44]. GCAM-Chile operates as a dynamic model and runs at 5-year time intervals from 2010 (calibration year) to 2100. GCAM-Chile integrates 33 geopolitical regions, capturing global interactions across energy, socio-economic, climate, water, and land systems, with the latter represented at a resolution of 0.5×0.5 degrees. Radiative forcing and climate effects of 24 GHGs, aerosols, and short-lived species are integrated into GCAM-Chile through the use of Hector, a climate carbon-cycle model [45, 46, 47, 48, 49].

GCAM-Chile was built, as mentioned above, from the base version of GCAM v6.0, where Latin America is represented through Colombia, Argentina, and Brazil as independent energy-economy regions, with two aggregate regions: South America Northern (French Guiana, Guyana, Suriname, Venezuela) and South America Southern (Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay). Hence, Chile was separated from the South America Southern region, resulting in the expansion to 33 energy and macroeconomic regions (see Figure 1). This process follows the methodology delineated by the Pacific Northwest National Laboratory [50], which served as the basis for developing other regional variants of GCAM, such as GCAM-USA [51] and GCAM-Korea [52]. The implementation of this methodology involves modifying the raw input files that define GCAM's regional structure through an R package developed by Khan et al. [53]. The disaggregation process also allocates existing water basins and land regions to the new region of Chile. This allows GCAM-Chile to perform the assessment of multi-sectoral energy supply and demand, including emissions within an integrated energy, economic, and climate modeling framework. The energy module in GCAM-Chile was calibrated using data from IEA's energy balances [54], with 2015 established as the base year. For the electricity sector, data from Chile's energy balance was used to calibrate electricity generation in 2020 [55], while also considering technology costs data from the Long Term Energy Planning (PELP) of Chile [56]. Regarding the economic sector, gross domestic product and population data from PELP were also employed to calibrate official data for Chile [56].

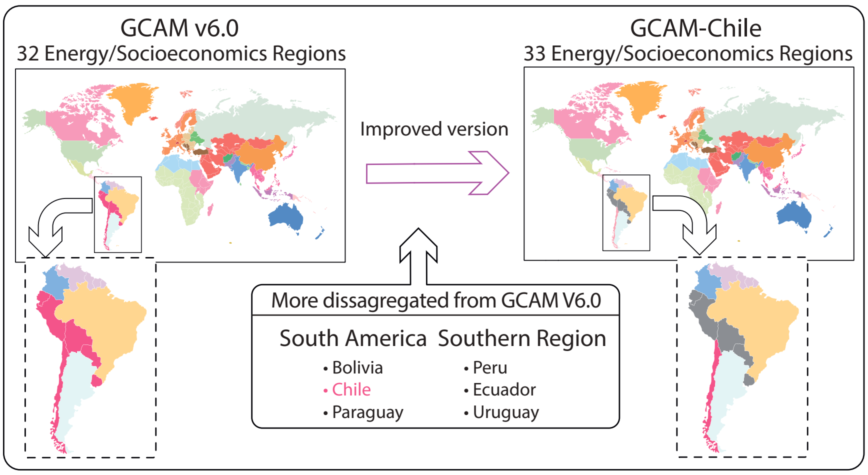


Figure 1: Disaggregation used in GCAM-Chile.

2.2. Deep-decarbonization: Statistical approach based on confidence intervals

This research defines deep-decarbonization pathways as those that achieve a level of emissions below the expected sequestration capacity of Chile by 2050. To properly define this, the expected sequestration must be defined. To do so, we compute the average historical sequestration capacity and its 95% confidence interval. Statistically, a confidence interval gives an estimated range of values which is likely to include an unknown parameter, where the estimated range is calculated from a given set of sample or historical data. Therefore, by using the history of the sequestration capacity of Chile, it is possible to estimate a range that would cover the sequestration capacity with a 95% chance. Technically, the confidence interval is estimated as $\bar{X} \pm Z\sigma/\sqrt{N}$, where $\bar{X}$ is the average historical sequestration capacity, σ is the standard deviation of the historical sequestration capacity, Z is the confidence level (following a Gaussian distribution), and N is the number of data points used to estimate the interval. Therefore, deep-decarbonization pathways are those that reach emissions below the lower bound (lower limit of the confidence interval), thereby, increasing the likelihood of achieving a net negative economy in Chile by 2050.

3. Estimate of Chilean sequestration capacity

The case study considers Chile's energy sector, specifically focusing on electricity generation and end-use sectors. Electricity generation level by technology for the 2015-2019 period was collected from the National Energy Commission [57]. In addition, data on the Chilean annual available sequestration capacity was collected from the Ministerio del Medio Ambiente [58]. In Chile, the land use sector is considered as the only source of negative emission, with a significant variability of 14 MtCO$_2$e (*sd*), which is high considering that its average has been 65 MtCO$_2$e. In 2018 land use corresponded to 36% (in absolute terms) of the GHG balance [58]. However, as shown in Figure 2, Chile's sequestration capacity has lately fallen well below its average, decreasing by 11.71 MtCO$_2$e due to, among others, wildfire events.

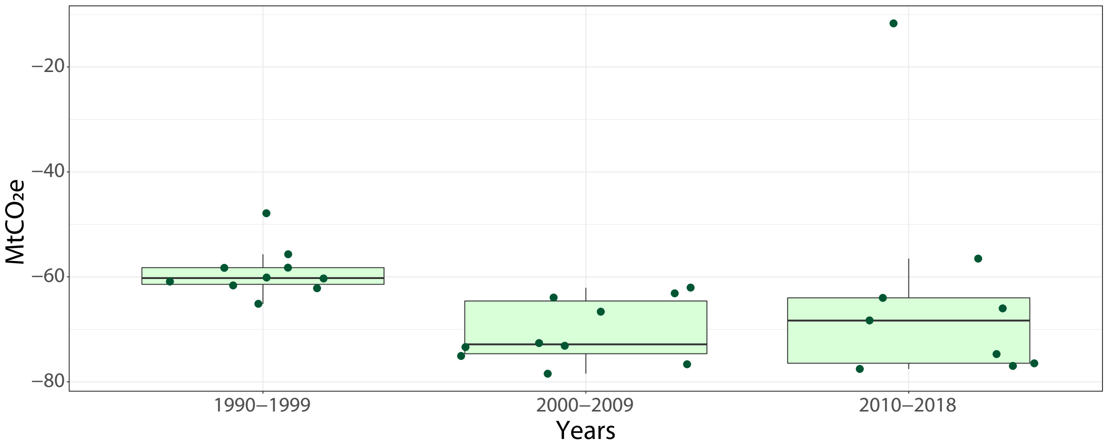


Figure 2: Historically available sequestration capacity of Chile.

Given the historical sequestration of Chile, as shown in Figure 2, the 95% confidence interval was estimated to be 65 ± 3.88 (65 [61;68]) MtCO$_2$e. Therefore, developing scenarios that can reach emissions levels below 61 MtCO$_2$e by 2050 yields scenarios that are likely to be net negative as the expected sequestration capacity ranges between 61 and 68 MtCO$_2$e. Hence, we focus our scenario analysis on such deep-decarbonization scenarios.

To assess deep-decarbonization scenarios (beyond what Chile considers a net neutral CO$_2$ level), we assess five MtCO$_2$e targets by 2050 that reach below the expected sequestration capacity interval. Hence, considering that the lower limit of the expected sequestration is 61 MtCO$_2$e, we evaluate scenarios that yield 60, 58, 56, 54, 52, and 50 MtCO$_2$e in 2050, hence, increasing the likelihood (falling outside the 95% confidence interval) of achieving carbon neutrality by further decarbonization of the energy sector. The scenarios are developed following all the NDC targets till 2030 and then linearly interpolating towards 2050 (from 2030) for the CO$_2$e emissions levels. Additionally, the Chilean green hydrogen strategy as well as the e-mobility strategies are considered. The phase out of coal-based power plants, as defined by the Chilean NDC, is modeled and are assumed to be decommissioned by 2040 and no new plants can be installed. Finally, the scenarios do not consider CCS, direct air capture (DAC), or other sequestration technologies. This is due to the fact that the Chilean PELP [56] does not foresee such technologies in their projections by 2050. Hence, we seek to propose net negative pathways based on technologies that are economically and technically feasible in the context of the Chilean PELP.

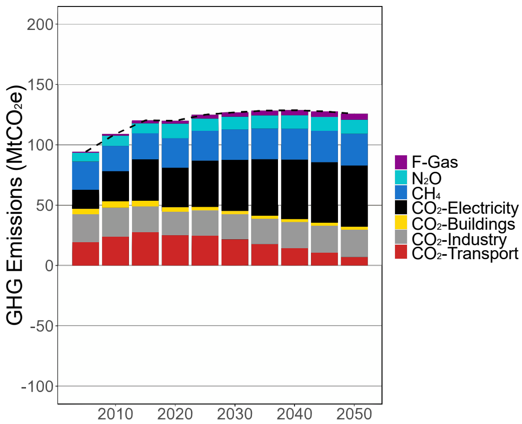
Table 1: Overview of scenarios

Scenario name	Emissions peak	Coal phase out	Buildings strategy	Hydrogen strategy	e-mobility strategy	GHG Target
Business As Usual	-	-	✓	✓	✓	None
NDC-65	2020	2040	✓	✓	✓	65
NDC-60	2020	2040	✓	✓	✓	60
NDC-58	2020	2040	✓	✓	✓	58
NDC-56	2020	2040	✓	✓	✓	56
NDC-54	2020	2040	✓	✓	✓	54
NDC-52	2020	2040	✓	✓	✓	52
NDC-50	2020	2040	✓	✓	✓	50

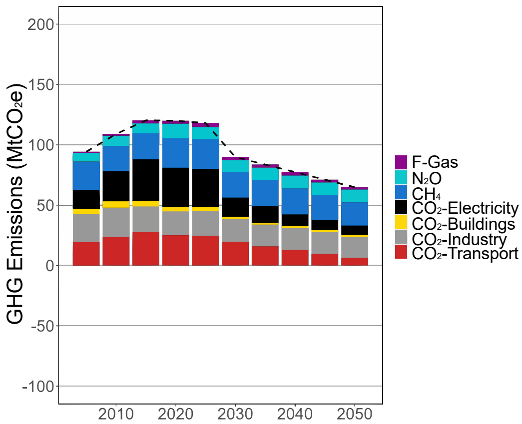
4. Results

4.1. Reference case and Chilean NDC

Figure 3 shows the GHG emissions projected by GCAM-Chile for both, the business as usual (BAU) case and NDC-65 (reference BAU scenario) in Chile by 2050. Under the BAU scenario (see Figure 3a), it can be noted that emissions steadily increased up until 2035-2040, with the main source of emissions coming from the electricity sector. This is mainly because this scenario does not consider the coal phase out policy, assessing what would happen if this commitment is not fulfilled. It can also be seen that emissions from the transportation sector are reduced, driven by e-mobility strategies (other sectors remain generally stable). On the other hand, as observed in Figure 3b, emissions peak in 2020 and decrease by 2050, reaching a level of 65 $MtCO_2e$, as indicated by the Chilean NDC. Most of the emissions reduction is observed in the electricity and transportation sectors. Note that, on average, Chile has had a sequestration level of 65 $MtCO_2e$, hence, this scenario would represent, in expectation, a carbon neutral case for Chile.



(a) GHG emissions for NDC-BAU scenario

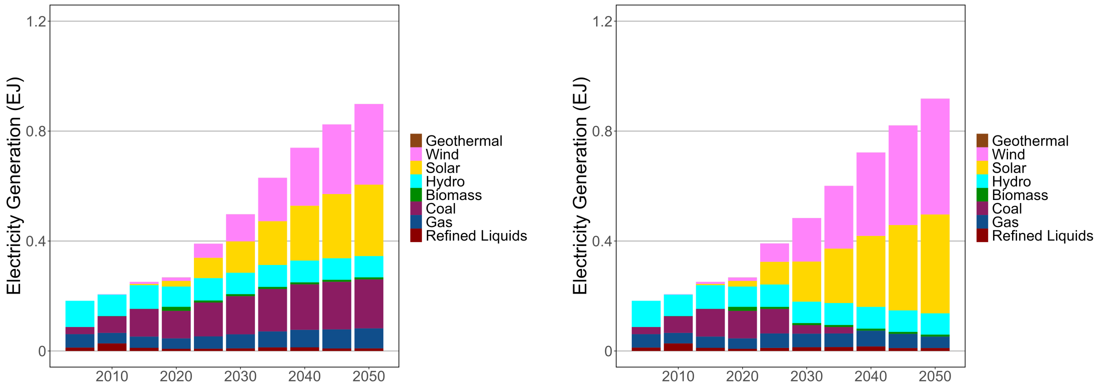


(b) GHG emissions for NDC-65 scenario

Figure 3: GHG emissions by sector

The difference in emissions from the electricity sector can be observed in Figure 4. Under the BAU scenario, there is a constant increase of fossil fuel-based electricity, mainly from coal followed by gas, even under the observable increase of wind, and solar energy. Wind and solar account for over 50% of the electricity generation in 2050, a share that increases if hydro-based electricity is considered. For the NDC-65 case (official Chilean NDC), there is a significant shift towards renewable energy. Solar, wind, and hydro account for almost all generation, with coal being phased out and natural gas supplying the required energy for balancing renewable sources. Further details regarding the power sector are discussed next.

4.2. Electricity generation



(a) Electricity generation for NDC-BAU scenario

(b) Electricity generation for NDC-65 scenario

Figure 4: Electricity generation by technology

Table 2 shows the total electricity generation by 2050 for all NDC scenarios (NDC-65, the original Chilean NDC up to NDC-50, the NDC policies with a deeper CO_2e emissions target by 2050). For the different scenarios considered, the results only show differences from 2030 onward, with those scenarios with a stringent CO_2e target reaching a higher level of electricity generation (reaching up 8.04% increase in the NDC-50 scenario compared to the NDC-65 scenario). The increased electricity generation level is required to further electrify end-use sectors (transport, buildings, industry, mining) required to achieve a deeper decarbonization.

Table 2: Electricity generation (EJ) by scenario

Scenario	2010	2015	2020	2025	2030	2035	2040	2045	2050
NDC-65	0.217	0.271	0.286	0.411	0.501	0.616	0.732	0.828	0.923
NDC-50	0.217	0.271	0.286	0.411	0.501	0.617	0.743	0.862	0.998
NDC-52	0.217	0.271	0.286	0.411	0.501	0.617	0.741	0.855	0.985
NDC-54	0.217	0.271	0.286	0.411	0.501	0.617	0.740	0.849	0.973
NDC-56	0.217	0.271	0.286	0.411	0.501	0.616	0.738	0.843	0.963
NDC-58	0.217	0.271	0.286	0.411	0.501	0.616	0.737	0.839	0.954
NDC-60	0.217	0.271	0.286	0.411	0.501	0.616	0.736	0.834	0.945

As expected, a significant reduction of CO_2e emissions (see Figure 3b) requires important electrification of demand sectors. However, such electrification must come together with a transformation of the electricity sources, particularly increasing generation of the share of renewable sources such as wind, solar, hydro, geothermal, and biomass. Figure 5 shows the electricity generation by source for all scenarios, clearly depicting the replacement of fossil technologies by renewable sources. Figure 5 clearly shows that it is indeed possible to phase out coal-based power plants by 2040. As coal is phased out, the share of wind and solar generation increases (mainly proportionally) towards 2050. Hydro-based electricity remains stable over the planning period, considering the current uncertainty regarding water availability and dry seasons. Other renewable sources, such as geothermal and biomass are not fully deployed given the fact that, on one side, biomass is not highly available for power generation in Chile (mainly used for heating in southern regions), while in the case of geothermal, there are still several concerns regarding its cost and safety on the Andes mountain chain (highly volcanic and with large earthquake activity).

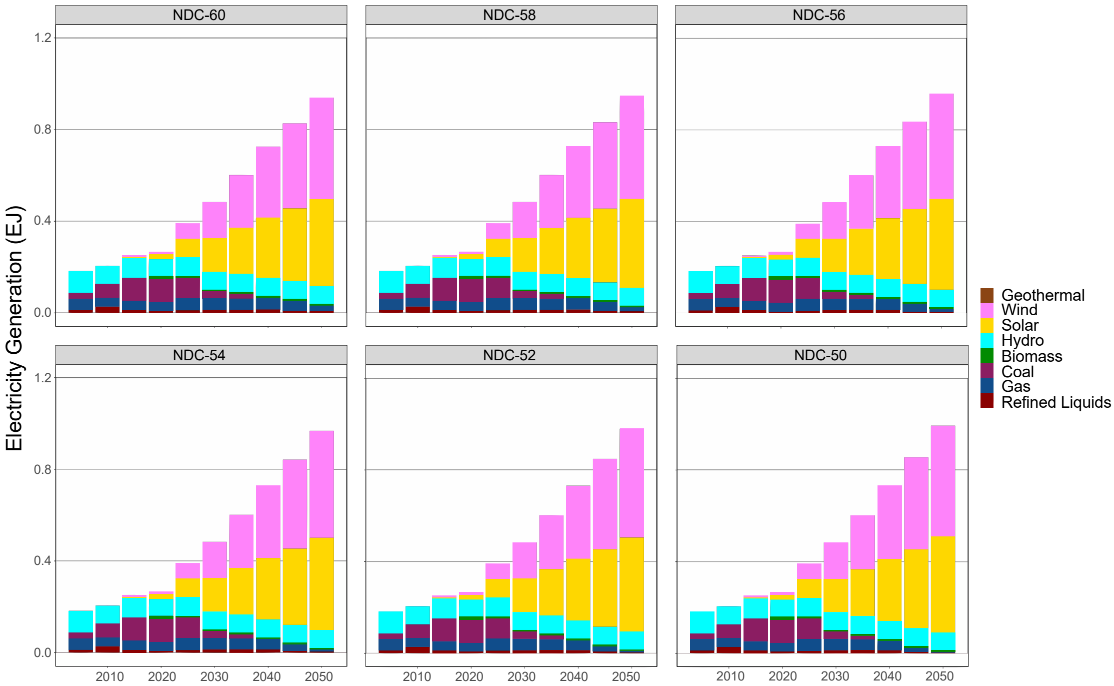


Figure 5: Electricity generation by technology - all scenarios

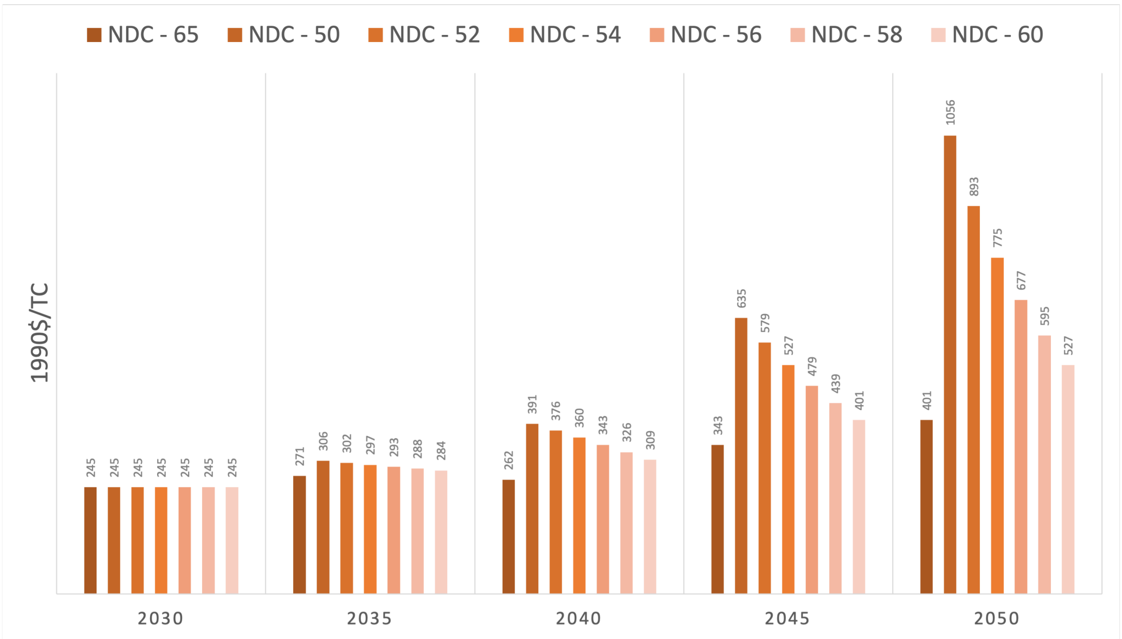


Figure 6: CO_2 prices across scenarios

Nevertheless, it is also important to note that when the base NDC scenario (NDC-65) is compared to the most stringent scenario (NDC-50), natural gas also suffers an important reduction, being almost phased out in 2050 in the NDC-50 scenario, going from a 5% share in 2050 for the NDC-65 scenario to a 0.3% share in 2050 for the NDC-50 case. The lower level of fossil fuels for electricity generation is a direct result of the imposed carbon limits for each scenario. The CO_2e tax required to reach such limits is shown in Figure 6. Figure 6 shows the costs, in terms of dollars per tonne of carbon (1990 USD), associated with achieving different levels of CO_2e emissions reduction targets. As expected, the carbon tax increases as the emissions reduction targets become more stringent. For example, NDC-65 incurs the lowest cost, while NDC-50 requires a significantly higher taxation scheme, reaching up to 1056 1990USD per tC. The results suggest that achieving more ambitious emissions reduction targets come with increased financial implications. These costs are likely influenced by factors such as the scale of emission reductions required, the chosen mitigation strategies, and the availability and effectiveness of technological solutions.

4.3. *Decarbonization of final demand sectors*

As already described, all NDC scenarios show an increased level of electricity generation when compared to both, the BAU case and the reference NDC scenario (NDC-65). The increased electricity generation, mainly from renewable sources, is used to reduce fossil fuel use in the final demand sectors by clean electricity. The level of electricity participation (electrification) in demand sectors in the year 2050 is shown in Table 3. As it can be noted, all scenarios show a significant increase of electricity use compared to the BAU case.

Table 3: Electrification (% of demand supplied by electricity) of final demand sectors in 2050.

Sector	BAU	NDC-65	NDC-60	NDC-58	NDC-56	NDC-54	NDC-52	NDC-50
Industry	55.4	61.9	63.8	64.7	65.6	66.7	67.9	69.0
Buildings	52.5	54.3	55.8	56.3	56.8	57.3	57.8	58.0
Mining	69.5	71.0	71.8	72.1	72.5	73.0	73.5	74.0
Transport	39.2	45.8	48.7	50.1	51.5	53.1	54.7	56.0

In the absence of CO_2e emissions reduction policies, the mining sector demonstrates a substantial reliance on electricity, accounting for nearly 70% of its energy consumption by 2050. This proportion only slightly increases to 74% in the NDC-50 scenario, highlighting the challenges of achieving significant electrification in mining due to the energy-intensive nature of certain processes requiring high temperatures. Conversely, the transportation sector proves to be challenging to fully electrify. Without any policies in place (BAU case), electricity usage in 2050 constitutes around 40% of the total energy demand for transportation. Under the NDC-65 scenario, the electrification rate rises to 46% (0.13 EJ) by 2050. However, in more ambitious decarbonization scenarios, the electrification levels for transport range from 48.7% in NDC-60 to 56% in NDC-50, suggesting potential for further electrification if lower emissions targets are pursued. Additionally, it is important to note that hydrogen use in the transport sector also takes an important share by 2050, as shown in Figure 7. Hence, although transport can not be fully electrified, a combined policy of use of electricity and hydrogen provides a feasible pathway towards a decarbonization of the transportation sector, as shown in Figure 8. In other sectors, industry shows electrification rates ranging from 63.8% to 69%, while buildings exhibit rates between 55.8% and 58% for NDC-60 and NDC-50, respectively.

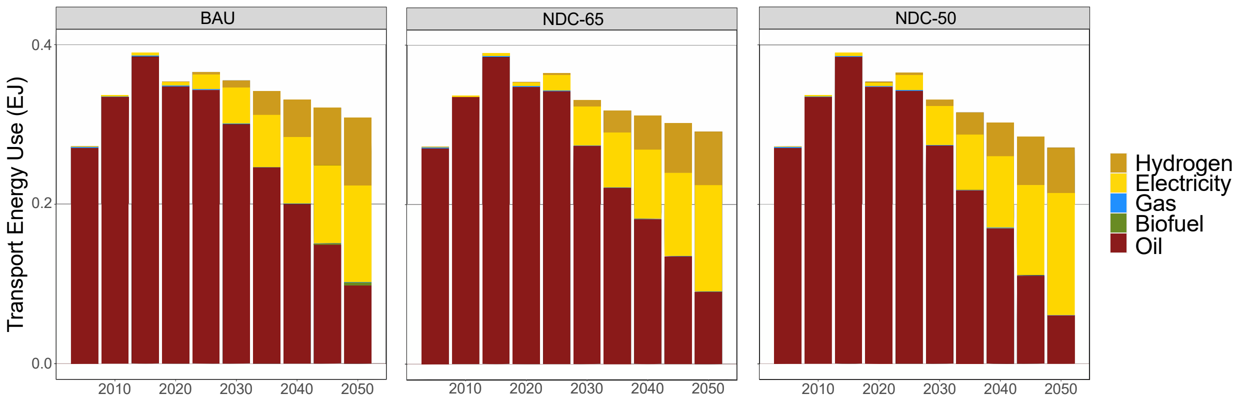


Figure 7: Transportation energy use

Table 4: Final energy use by sector and fuel for NDC-65 scenario (EJ)

Sector	Fuel	2025	2030	2035	2040	2045	2050
Industry	Gas	0.035	0.035	0.034	0.033	0.032	0.030
	Hydrogen	0.000	0.000	0.001	0.003	0.004	0.005
	Electricity	0.092	0.121	0.173	0.229	0.266	0.295
	Refined liquids	0.088	0.086	0.084	0.082	0.080	0.083
	Biomass	0.196	0.183	0.154	0.106	0.078	0.061
	Coal	0.011	0.009	0.006	0.004	0.003	0.003
	Traditional biomass	0.000	0.000	0.000	0.000	0.000	0.000
Buildings	Gas	0.018	0.012	0.013	0.016	0.014	0.012
	Hydrogen	0.000	0.000	0.000	0.000	0.000	0.000
	Electricity	0.140	0.154	0.172	0.198	0.224	0.249
	Refined liquids	0.027	0.018	0.014	0.015	0.012	0.013
	Biomass	0.013	0.018	0.026	0.011	0.004	0.002
	Coal	0.000	0.000	0.000	0.000	0.000	0.000
	Traditional biomass	0.181	0.194	0.198	0.194	0.191	0.183
Mining	Gas	0.005	0.002	0.001	0.001	0.000	0.000
	Hydrogen	0.004	0.009	0.016	0.018	0.019	0.019
	Electricity	0.118	0.127	0.136	0.140	0.143	0.148
	Refined liquids	0.093	0.076	0.059	0.053	0.046	0.041
	Biomass	0.000	0.000	0.000	0.000	0.000	0.000
	Coal	0.001	0.000	0.000	0.000	0.000	0.000
	Traditional biomass	0.000	0.000	0.000	0.000	0.000	0.000
Transport	Gas	0.001	0.001	0.001	0.000	0.000	0.000
	Hydrogen	0.003	0.009	0.028	0.043	0.062	0.067
	Electricity	0.019	0.048	0.069	0.087	0.104	0.133
	Refined liquids	0.342	0.274	0.221	0.182	0.135	0.091
	Biomass	0.000	0.000	0.000	0.000	0.000	0.000
	Coal	0.000	0.000	0.000	0.000	0.000	0.000
	Traditional biomass	0.000	0.000	0.000	0.000	0.000	0.000

Table 4 shows further details regarding fuel usage by demand sector for the NDC-65 case (reference NDC). As mentioned in Table 3, the mining sector shows an important level of electricity use, reaching 71% share. However, if green hydrogen is added as a clean fuel, the share of electricity and hydrogen in mining reaches 80%. A similar trend can be observed in other sectors, particularly in the transport sector. Hydrogen in transport reaches 23% share in 2050, showing that only 31% of the final transport demand is covered by fossil fuels (refined liquids, mainly). When compared to the NDC-50 scenario, the share of fossil fuel drops drastically from 31% (NDC-65) to 22% (NDC-50).

The results shown in Table 4 indicate that some sectors can be further decarbonized (either electrified or upgraded to hydrogen usage) to achieve a lower level of CO_2e emissions, hence significantly increasing the chances of reaching carbon neutral scenarios by 2050, or even further, a net negative economy-wide system by 2050 in Chile.

4.4. Emission reduction pathways and remaining sources

As described in the previous section, many end-use sectors are significantly electrified. However, some hard-to-decarbonize (hard to abate) sectors, such as industry and transport, still rely on fossil fuels by mid-century in all of the NDC scenarios. As shown in Figure 8, CO_2 emissions from the electricity sector are significantly reduced (also discussed in previous sections). However, some non-electricity sector GHG emissions still remain, particularly industrial and transport-related emissions. Also, methane emissions (CH_4) and N_2O emissions have an important contribution in 2050, even in the most stringent scenario (NDC-50).

Regarding the levels of CO_2 emissions alone, they range between 33.14 $MtCO_2e$ (NDC-65) and 20.01 $MtCO_2e$ (NDC-50) in 2050, representing almost a reduction of 40% between the NDC-65 scenario and the most conservative

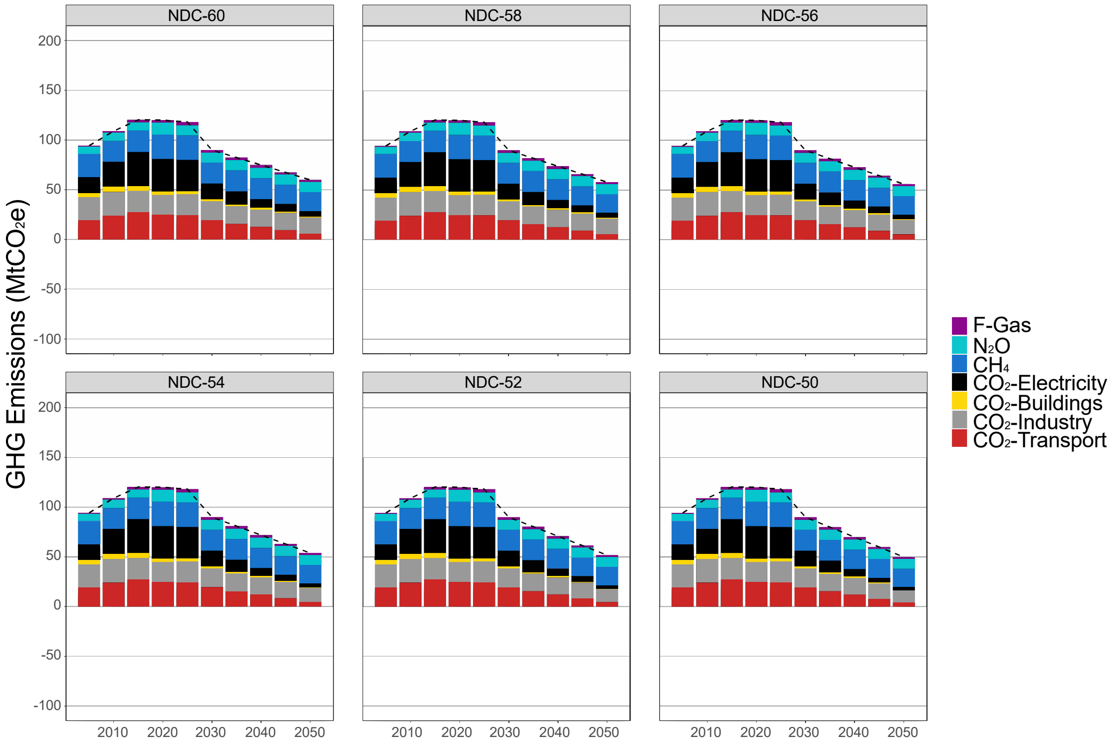


Figure 8: GHG emissions across scenarios

NDC-50 scenario. This reduction of 40% translates into the need for significantly higher carbon prices, as discussed previously and shown in Figure 6. The industrial sector accounts for roughly 50% of the remaining CO_2 by 2050 in the NDC-50 scenario (most likely to be net negative), of which the two most intensive sectors are the cement and mining industries, contributing 11% and 12% of the industrial sector CO_2 emissions, respectively.

Non-CO_2 emissions significantly contribute to the GHG levels by 2050 in all scenarios. Particularly, CH_4 and N_2O emissions are the most emitted non-CO_2 gases. Table 5 shows the CH_4 emissions by source in 2050 for each scenario. Methane emissions are modeled separately for energy/industrial/urban (CH_4), agricultural CH_4 (CH_4 AGR), and CH_4 from agricultural waste burning (CH_4 AWB). Agricultural CH_4 emissions account for almost 38% of the total CH_4 emissions in 2050 (on average across scenarios) while energy/industrial/urban accounts for 62% of it. Total methane emissions are 5.5% lower in the NDC-50 scenario compared to the NDC-65 case. These reductions mainly occur in methane emissions produced in the energy/industrial/urban sectors. Indeed, when the NDC-50 case is compared to the NDC-65, there is an 8% reduction in CH_4 emissions. The two sub-sectors within energy/industrial/urban sectors that emit the most are heating (residential) and urban processes, with 85% (on average) of CH_4 emissions being produced by urban processes and 10% by residential heating. Regarding methane emissions from the agricultural sector, production of beef, dairy, and pork accounts for over 92% of the CH_4 emissions in 2050 in all scenarios. Finally, regarding CH_4 AWB emissions, wheat, corn, and fruit are associated with a higher level of emissions, accounting to 32%, 22% and 6% (on average) of the CH_4 AWB emissions, respectively.

Nitrous oxide emissions (N_2O), is the most significant after CH_4 emissions by 2050. Contrary to the CH_4 emissions, as Table 6 shows, N_2O are mostly generated by the agricultural sector (N_2O AGR), followed by the energy/industry/urban emissions. Agricultural N_2O emissions account for, on average across scenarios, 74% of the total N_2O in 2050, while energy/industry/urban N_2O emissions account for 25% (average). Similarly to CH_4 emissions, beef, dairy, pork, wheat, and fruit production are associated with higher levels of N_2O agricultural emissions, accounting for over 64% of the total N_2O emissions. Interestingly, regarding energy/industry/urban N_2O emissions, the sectors that emit the most are electricity, residential heating, industrial processes, and urban processes. Among these four emitting sectors, the only sector that significantly reduces its emissions in the NDC-50 scenario compared

Table 5: CH_4 Emissions in 2050 ($MtCO_2e$)

Scenario	**CH_4**	**CH_4 AGR**	**CH_4 AWB**	**Total CH_4**
NDC-65	11.79	6.90	0.05	18.74
NDC-50	10.82	6.84	0.05	17.71
NDC-52	10.95	6.85	0.05	17.85
NDC-54	11.05	6.86	0.05	17.96
NDC-56	11.13	6.87	0.05	18.05
NDC-58	11.20	6.88	0.05	18.13
NDC-60	11.26	6.89	0.05	18.20

to the NDC-65 is the electricity sector, reaching a reduction of almost 45%. All other three main emitting sectors remain fairly stable across the NDC scenarios.

Table 6: N_2O Emissions in 2050 ($MtCO_2e$)

Scenario	**N_2O**	**N_2O AGR**	**N_2O AWB**	**Total N_2O**
NDC-65	2.84	7.75	0.01	10.60
NDC-50	2.44	7.56	0.01	10.01
NDC-52	2.52	7.58	0.01	10.11
NDC-54	2.58	7.60	0.01	10.19
NDC-56	2.64	7.63	0.01	10.28
NDC-58	2.69	7.66	0.01	10.36
NDC-60	2.74	7.69	0.01	10.44

5. Conclusions and future research

This research is the first to present deep-decarbonization scenarios and their assessment of the Chilean energy system. Particularly, the focus is on scenarios that are below the expected level of sequestration capacity of Chile, which has been estimated by the Chilean government to be 65M $MtCO_2e$. Using historical emissions inventories, we estimated a 95% confidence interval for the sequestration capacity, reaching an interval ranging between 68 and 61 $MtCO_2e$ emissions. Hence, our focus is particularly on those scenarios that show a transition toward a system that results in emissions levels below the lower bound on the confidence interval (61 $MtCO_2e$). In this way, we can, statistically speaking, increase the chances of reaching a net neutral or net negative energy system (and economy-wide) by 2050.

The development and assessment of the scenarios is carried out using a new version of the state-of-the-art GCAM IAM. We particularly developed a regional version of the GCAM model that considers Chile as an individual energy-economy region within the global GCAM regions. This allows us to assess decarbonization pathways considering a higher disaggregation in the industrial sector, particularly assessing energy use and emissions from the mining sector, a key sector in the Chilean economy.

Results indicate that further decarbonization of the energy system, compared to that achieved under the actual Chilean NDC (to reach 65 $MtCO_2e$ emissions by 2050), is possible by further increasing the share of renewable electricity sources (wind and solar) as well as the net level of electricity to obtain higher levels of electrification rates in final demand sectors. Additionally, e-fuels, such as hydrogen, also provide important means to reduce emissions levels, particularly in the mining and transport sectors. The results also indicate that after the reduction of CO_2 emissions and decarbonization of the power sector, CH_4 and N_2O emissions remain the most prominent GHG, with industrial processes and the agriculture sector being the main sources of emissions. Therefore, decarbonization strategies beyond the energy sector are required to be aligned with long-term temperature targets and to reduce the dependency on sequestration capacity as currently assumed by the Chilean NDC. However, it is necessary to seek for the correct implementation means as the economical implications of deep-decarbonization of the Chilean economy appear to be significant. Indeed, carbon prices more than double by 2050 in the more stringent NDC scenario assessed in this research when compared to the current Chilean NDC.

Finally, the examination of alternative scenarios and sector-specific data offers useful insights into the energy situation and decarbonization activities. The findings illustrate the challenges and possibilities that come with switching to greener energy sources and lowering CO_2 emissions. These findings highlight the significance of developing targeted and comprehensive strategies to expedite the use of cleaner energy sources and encourage electrification in a variety of industries. Targeted measures to address the particular issues that each sector faces, such as high-energy processes in mining and the complex infrastructure of the transportation sector, will be critical for achieving significant emissions reductions and progressing toward a more sustainable future. It is important to note, however, that the assessment carried out in this research must be understood under the limitations of the modeling approach. For instance, GCAM, like several other IAMs, cannot assess variability associated with renewable sources. Therefore, transitions to greener economies based on renewable energy can be optimistic if no proper strategies to manage variability are implemented. Some of those relate to a higher level of flexibility in the energy system through battery storage, market integration, Power-to-X, or demand response, among other alternatives.

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Appendix A. Scenarios: Carbon sequestration technologies

This section presents some results regarding CCS and DAC technologies in the context of the scenarios described in Table 1. In particular, scenarios considering BECCS and DAC are evaluated considering the same budget scenarios presented before. Additionally, we perform a sensitivity on biomass availability in the power sector (with or without a ceiling) and on CCS cost (reference or low cost). The summary of scenarios is shown in Table A.7. Limits on biomass usage for electricity generation is considered due to the fact that biomass is not a technology that is well developed and planned in the long term strategy of Chile (PELP study). Scenarios based on biomass limits and CCS cost are built in order to assess the impact of a more favorable context for sequestration technologies. Hence, all scenarios of the Scenario set 1 are more stringent since they have a biomass ceiling for power generation (limited to the same amount of biomass used in 2020, reference case) and no reduced technology cost. On the other side, Scenario set 3 is the most favorable since it does not consider biomass limits and also considers a low cost for CCS technologies. In all scenarios, DACs were modeled considering reference technological data used in GCAM across all regions (global technologies database in GCAM).

Figure A.9 shows emissions levels for all 18 different runs (3 scenario sets with or without biomass limits and low or reference cost for CCS). Figure A.9 shows that Scenario set 3 (third column) makes higher use of BECCS (BioCCS label in Figure A.9) to offset slightly higher emissions levels. The offset of BECCS guarantees that the target GHG level in 2050 is reached. It can also be noted that the more stringent the NDC target (50 vs 60 $MtCO_2e$), the more BECCS is used to offset GHG emissions. Also, it is observed that CCS is used, however, DAC does not seem to be an important technology in the context of Chile. Actual CH_4 and N_2O emissions (compared with no-CCS scenarios in the main document) can be observed in Table A.8.

Figure A.10, Figure A.11, and Figure A.12 show the electricity generation for each scenario set and each GHG level, including the role of CCS combined with biomass, gas, and liquids. Since coal is phased out by 2040 in all scenarios, CCS combined with coal is never deployed (no scenario opted for this technology). CCS is deployed mostly with biomass, particularly in Scenario set 3, where no limit on biomass usage for electricity generation is present. When limits are considered, CCS with gas or liquids is present.

Table A.7: Scenarios denomination and characterization

Scenario set	**NDC GHG target**	**Bio ceiling**	**CCS cost**	**Nomenclature**
Scenario 1	50	✓	Reference	SCE1 - 50
Scenario 1	52	✓	Reference	SCE1 - 52
Scenario 1	54	✓	Reference	SCE1 - 54
Scenario 1	56	✓	Reference	SCE1 - 56
Scenario 1	58	✓	Reference	SCE1 - 58
Scenario 1	60	✓	Reference	SCE1 - 60
Scenario 2	50	✓	Low	SCE2 - 50
Scenario 2	52	✓	Low	SCE2 - 52
Scenario 2	54	✓	Low	SCE2 - 54
Scenario 2	56	✓	Low	SCE2 - 56
Scenario 2	58	✓	Low	SCE2 - 58
Scenario 2	60	✓	Low	SCE2 - 60
Scenario 3	50		Low	SCE3 - 50
Scenario 3	52		Low	SCE3 - 52
Scenario 3	54		Low	SCE3 - 54
Scenario 3	56		Low	SCE3 - 56
Scenario 3	58		Low	SCE3 - 58
Scenario 3	60		Low	SCE3 - 60

Table A.8: CH_4 and N_2O Emissions in 2050 ($MtCO_2e$)

Scenario	CH_4	CH_4 AGR	CH_4 AWB	Total CH_4	N_2O	N_2O AGR	N_2O AWB	Total N_2O
SCE1 - 60	12.26	6.95	0.05	19.26	2.24	7.95	0.01	10.20
SCE1 - 58	11.73	6.93	0.05	18.71	2.21	7.91	0.01	10.13
SCE1 - 56	11.38	6.92	0.05	18.35	2.18	7.89	0.01	10.08
SCE1 - 54	11.09	6.92	0.05	18.06	2.15	7.89	0.01	10.05
SCE1 - 52	11.03	6.91	0.05	17.99	2.11	7.89	0.01	10.01
SCE1 - 50	10.97	6.91	0.05	17.93	2.09	7.88	0.01	9.98
SCE2 - 60	12.30	6.95	0.05	19.30	2.36	7.85	0.01	10.22
SCE2 - 58	11.76	6.93	0.05	18.74	2.32	7.81	0.01	10.14
SCE2 - 56	11.39	6.92	0.05	18.36	2.27	7.80	0.01	10.08
SCE2 - 54	11.10	6.92	0.05	18.07	2.22	7.80	0.01	10.03
SCE2 - 52	11.03	6.91	0.05	17.99	2.17	7.79	0.01	9.97
SCE2 - 50	10.96	6.91	0.05	17.92	2.12	7.79	0.01	9.92
SCE3 - 60	13.93	6.97	0.05	20.95	4.68	7.92	0.01	12.61
SCE3 - 58	13.64	6.96	0.05	20.65	4.35	7.91	0.01	12.27
SCE3 - 56	13.33	6.95	0.05	20.33	4.05	7.89	0.01	11.95
SCE3 - 54	13.01	6.94	0.05	20.00	3.78	7.87	0.01	11.66
SCE3 - 52	12.66	6.93	0.05	19.64	3.54	7.85	0.01	11.40
SCE3 - 50	12.30	6.92	0.05	19.27	3.33	7.83	0.01	11.17

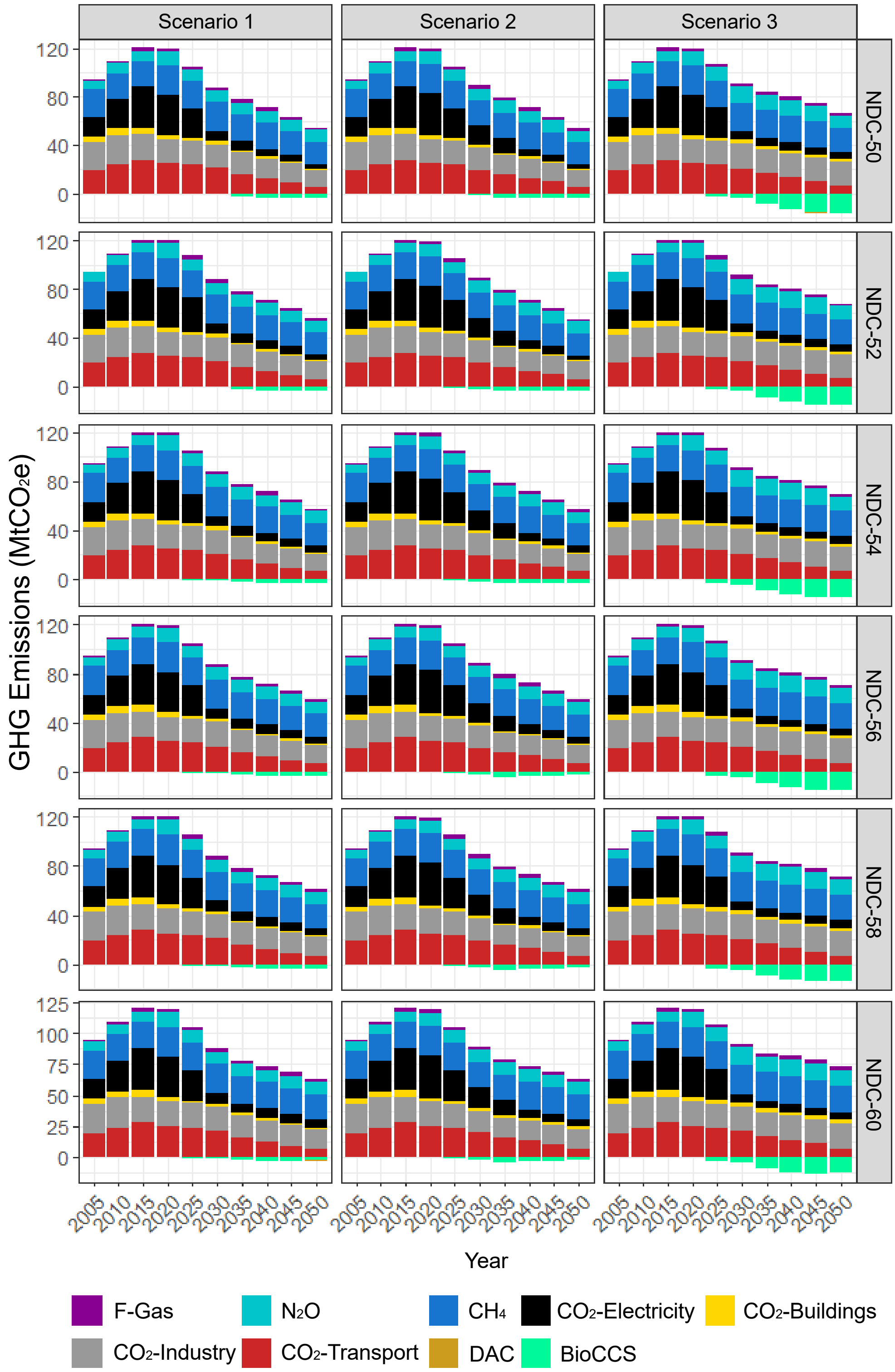

Figure A.9: GHG emissions across the BEECS scenarios

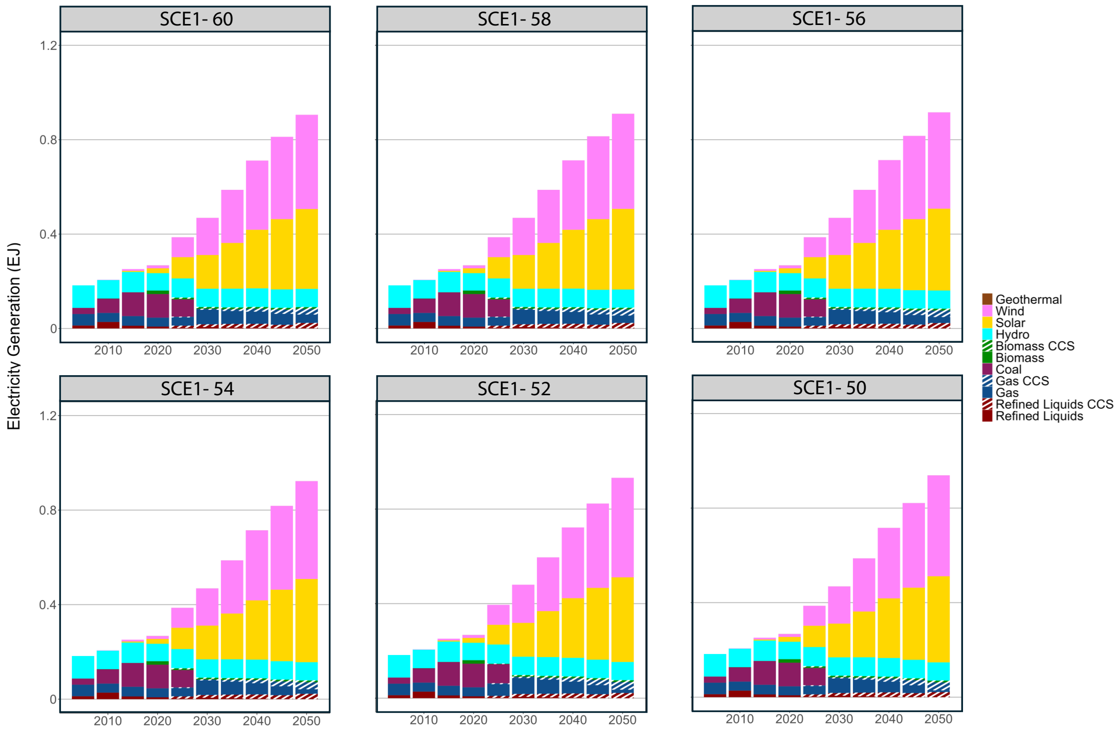

Figure A.10: Electricity generation by technology - Scenario 1

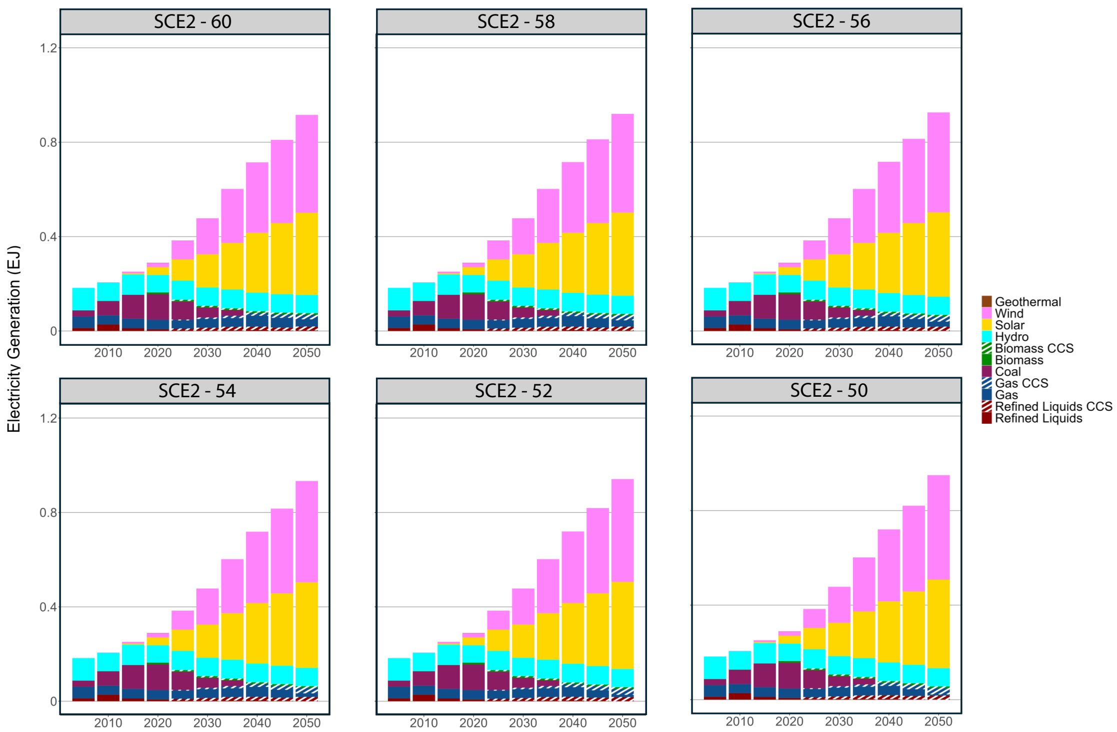

Figure A.11: Electricity generation by technology - Scenario 2

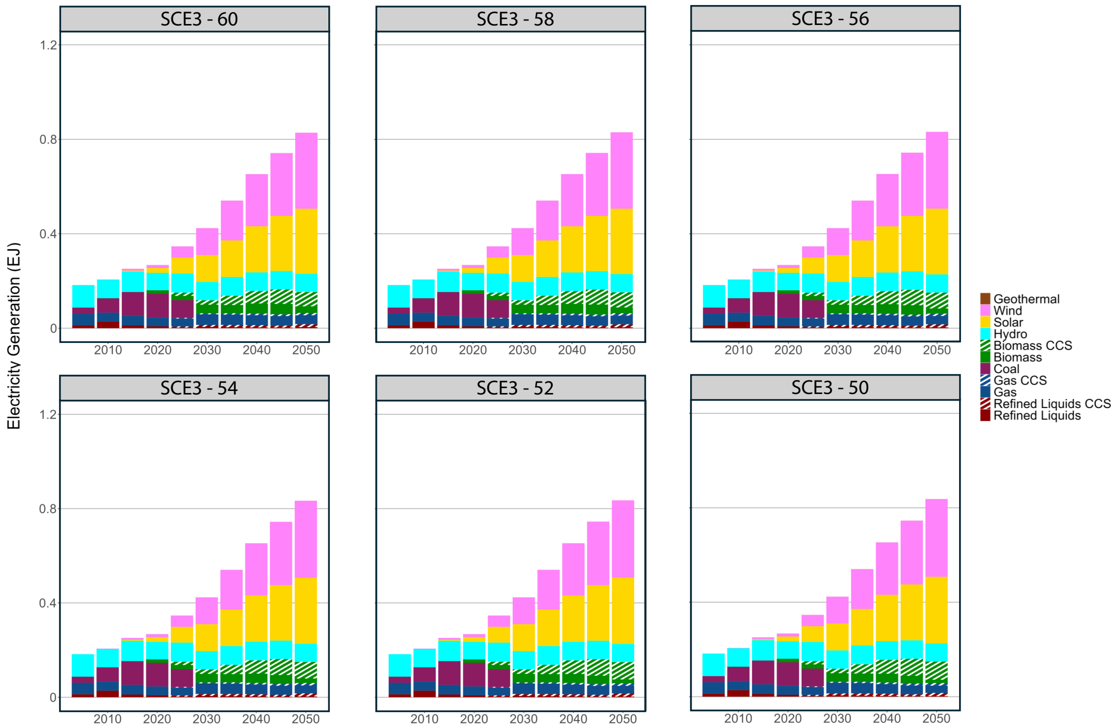

Figure A.12: Electricity generation by technology - Scenario 3

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