Assessment of the Impacts of Renewable Energy Variability in Long-term Decarbonization Strategies

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Abstract

To meet the nationally determined contributions proposed by the countries that signed the Paris Agreement, investments must be made in renewable generation technologies such as solar and wind. However, due to their high variability, these technologies pose challenges in terms of meeting demand or generating excess electricity. For this reason, energy system models are designed to capture this variability by considering flexibility technologies. Nevertheless, it is important to note that some energy system models lack integration with other sectors. Therefore, integrated assessment models have been employed to evaluate mitigation strategies, as they endogenously consider the linkages between energy and non-energy sectors. In addition, due to their complexity, these models do not account for the variability of renewable resources. Hence, this research aims to address this issue. This work represents the first attempt to evaluate how the introduction of hourly resolution affects the outcomes of integrated assessment models, specifically focusing on the Global Change Analysis Model (GCAM). We employ a soft-linking approach between the GCAM and the Highway to Renewable Energy Systems model (H2RES, an hourly level energy system model) to accomplish this. The proposed approach is tested using Chile's Nationally Determined Contributions under different hydrological profiles in the power sector. The results show that it is possible to use the capacity obtained from the Global Change Analysis Model and implement it on an hourly scale. However, the feasibility of implementation depends on high levels of flexibility technologies, such as battery energy storage. When given the choice of investments in renewable sources and flexible technologies, the optimal dispatch of the H2RES model show small differences than those obtained by GCAM-Chile. H2RES differs from GCAM-Chile in approximately 5% for wind and 3% for solar electricity generation in the year 2050. However, feasible integration of significant renewable sources is obtained with relatively high Critical Excess Electricity Production levels, reaching 20% in 2050. This excess electricity is attributed to the necessity for flexible technologies to manage the intermittency of renewables sources when hourly profiles of such sources are considered.

Keywords: Carbon neutral, Energy transition, Decarbonization, Integrated assessment model, GCAM, H2RES

Acronyms

BAU Business As Usual.

CCS Carbon Capture and Storage.

EDGE-T Energy Demand Generator Model for the Transport Sector.

ESM Energy System Models.

GCAM Global Change Analysis Model.

GHG Greenhouse Gases.

H2RES Highway to Renewable Energy Systems.

HDAM Hydro-dam.

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HPHS Hydro-pump.

HROR Run of the river hydro.

IAMs Integrated Assessment Models.

LEAP Long-range Energy Alternatives Planning System.

LEELO Long-term Energy Expansion Linear Optimization.

LULUCF Land Use, Land-use Change, Forestry.

MESSAGE Model of Energy Supply Strategy Alternatives and their General Environmental Impacts.

NDC Nationally Determined Contribution.

OSeMOSYS Open Source energy MOdelling SYStem.

ReMIND Regional Model of Investment and Development.

RLDC Residual Load Duration Curve.

RPS Renewable Energy Penetration Standards.

SSP2 Shared Socioeconomic Pathway 2.

WEF Water-Energy-Food.

1. Introduction and literature review

The Paris Agreement aims to keep temperature levels well below 2°C and to make additional efforts to limit the temperature increase even further to 1.5°C from pre-industrial levels. Currently, there are studies specifically focused on achieving the 1.5°C target [1, 2]. To achieve this target, it is necessary to decarbonize the energy, buildings, and transport sectors, which are the main ones responsible for Greenhouse Gases (GHG) emissions [3, 4]. Most countries that signed the agreement in 2015 later ratified their commitments, known as Nationally Determined Contribution (NDC) [5, 6]. In addition, countries have been implementing different strategies to achieve GHG emissions reductions, such as cap-and-trade mechanisms [7] or carbon tax [8]. In 2022, The most prominent target in the countries' NDCs is to achieve carbon neutrality (Net-zero target) before 2050-2070 to accelerate the decarbonization of the above systems [9]. However, authors find that in some countries, NDC are ineffective in achieving success in complying with the Paris Agreement [10, 11]. Therefore, countries must commit to more significant decarbonization efforts such as carbon net negative and work towards 100% renewable energy systems [12].

Decarbonizing the energy system is a fundamental and complex challenge when coupled with other systems, such as water and food-land, known as the Water-Energy-Food (WEF) nexus. For example, when contemplating the WEF nexus, Burrow et al. [13] consider the impact of nexus decisions related to water and power generation. They developed an optimization model for this goal that minimizes the costs of mitigating water scarcity in agriculture and facilitates thermal power generation. On the other hand, different studies have shown that electrification in different sectors, such as buildings and transportation, is a viable alternative for decarbonization [14, 15]. However, the increase in electricity generation may face risks due to water scarcity, which is projected to increase towards 2050 [16]. Therefore, it is necessary to increase renewable energy penetration to target 100% renewable energy systems. However, increased levels of renewable generation bring challenges associated with handling uncertainty or high variability of renewable resources to guarantee the balance of supply and demand, resulting in unsatisfied demand or significant excess of renewable energy [17].

In the context of 100% renewable energy systems, standalone energy system models cannot develop decarbonization strategies accounting for interactions with other non-energy systems, such as land-use (e.g., agriculture and livestock) systems, which is a sizeable emitting sector. Literature has proposed using Integrated Assessment Models (IAMs) to handle this issue. For example, Vuuren et al. [18] discovered that to keep global temperatures below 2°C, GHG emissions must be reduced by 70% by 2100. Feijoo et al. [19] used the Global Change Analysis Model (GCAM), a leading IAM, where they evaluate 5000 different mitigation scenarios, of which 23% of the scenarios that include Carbon Capture and Storage (CCS) technologies achieve a temperature target of 1.5 °C. In addition, Feijoo et al. [20] used a U.S. regional version of GCAM (GCAM-USA), where strict carbon budget scenarios are evaluated, resulting in the decarbonization of demand sectors such as industry and buildings. Similarly, Jeon et al. [21] disaggregated Korea as a GCAM-independent region (GCAM-Korea). GCAM-Korea subdivided the Korean energy system into 16 zones. The authors compared their results with historical values for Korea at the provincial level and concluded that GCAM-Korea could be used to develop energy plans at the regional level. Another example of a GCAM disaggregation is GCAM-Latin America (GCAM-LA), one of the first IAM models that consider each region of Latin America as an independent region. It is a modified version of GCAM Latin America and the Caribbean (GCAM-LAC); GCAM-LAC has desegregated Colombia, Argentina, Brazil, and Uruguay as independent regions but contained a group of countries as part of a South American Southern region [22]. Arriet et al. [23] used GCAM-LA to evaluate alternative decarbonization strategies to those proposed by the Chilean NDC. Their results show that despite having a five-year delay in phasing out coal, carbon neutrality can be achieved by incurring a higher capital cost in the electricity sector. Then, Matamala et al. [24] used a novel approach for risk assessment of the probability of achieving Chilean NDC due to uncertainty in sequestration levels. Their focus was the integration of the GCAM-LA and the chance constraint. The authors show that Higher likelihood levels extend 100% renewable electrical systems.

An updated version of an IAM for Chile is the Global Change Analysis Model for Chile (GCAM-Chile) [25]. Other regional versions of GCAM have already been developed, such as GCAM-USA [26] and GCAM-China [27]. All these versions simultaneously analyze interactions between population, economic growth, energy, land, and water resources under different policy settings, such as carbon tax and budget. For example, Khan et al. [28] utilized GCAM-USA to examine disaggregated profiles of intra-annual electricity demand. Specifically, they performed a dynamic disaggregated Profile with twenty-five segments for each end-use sector (transportation, industry, building).

Another commonly used IAM is the Regional Model of Investment and Development (ReMIND) model [29]. For example, Ueckerdt et al. [30] developed a distant perspective to represent the integration of renewable resources (solar and wind) in IAMs - The Residual Load Duration Curve (RLDC). Its approach provides a more accurate view of the system-level impacts of variable renewables and, thus, a more robust perspective on the decarbonization of the electricity sector and its economic consequences. Besides, Rottoli et al. [31] made a coupling of the ReMIND model with the Energy Demand Generator Model for the Transport Sector (EDGE-T). Their case study was the pathway to Europe; the authors show that there will be a decrease in emissions in the transport sector due to the electrification of the sector despite the increase in demand for transport services (passenger and freight). Another example is proposed by [32], where Lithuanian energy scenarios were modeled with the Model of Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE). Their results show that having high import prices can lead to an increase in domestic electricity generation in Lithuania. However, these policies cannot be considered an option because they negatively influence economic development.

Besides the abundant literature on IAM, they usually do not consider the variability associated with renewable energy sources, such as the availability of solar and wind power [33]. Likewise, they generally do not consider flexible technologies (Power-To-X) to assess the balancing of supply and demand when increased levels of renewable power are present. These Power-To-X technologies have already been used and have become a feasible solution in different demand sectors, such as the heating [34], and cooling [35], or transport sectors [36]. On the other hand, there are Energy System Models (ESM) that can consider the hourly variability of renewable resources. For example, Krajačić et al. [37] used Highway to Renewable Energy Systems (H2RES) to model and plan the electrical system of an island. Similarly, the authors of [38] developed a new long-term energy planning model that is an updated version of the H2RES model presented in [37, 39]. They evaluated alternative policies for CO_2 targets and levels of renewable energy sources in the decarbonization of the Croatian energy sector. Their results show that flexible technologies (Power-to-X) provide lower critical excess energy production levels. However, fossil fuels continue contributing to the transportation sector despite the electricity sector reaching 90% renewable energy levels by 2050. Prina et al. [40] uses a model based on EnergyPLAN applied to the Italian case. Their results show that 24% of emissions are reduced with wind power, batteries, and residential photovoltaics. However, when electric mobility is added, there is a cumulative reduction of 30%. Likewise, Lund et al. [41] used EnergyPLAN to design an energy transition strategy in Denmark to achieve a fully decarbonized energy system by 2045. In addition, Other authors, such as Groppi et al. [42], use the Open Source energy MOdelling SYStem (OSeMOSYS) to evaluate different energy policies to visualize how they affect an island's long-term energy strategy. Their results show that a carbon tax covering maritime transportation reduces cumulative global emissions. In addition, the authors show that models with hourly resolution generate better results than models with lower temporal resolution, i.e., grouping periods.

The ESMs described above do not consider the interaction with other non-energy systems such as Land Use, Land-use Change, Forestry (LULUCF), Water, or Climate systems. Therefore, there is no synergy, and consequently, it is not possible to quantify the benefits or impacts that the implemented long-term energy planning would cause. This is critical for some countries in the context of their NDC. For instance, Chile declares that in order to achieve carbon neutrality, roughly 50% of their current emissions will be captured by forests or other sinks by 2050. Therefore, this paper focuses on assessing the decarbonization of the Chilean energy system with GCAM-Chile (to account for energy and non-energy synergies) and assessing the results with an hourly-based energy model to guarantee that solutions are viable at an operational level. This is novel since previous studies have not developed such an integrated assessment. For instance, Haas et al. [43] used the Long-term Energy Expansion Linear Optimization (LEELO) model to evaluate the Chilean power system in 2050, focusing on storage requirements needed to achieve 100% renewable power system. Amigo et al. [44] implemented a cap-and-trade model to assess the goals proposed in the Chilean NDC. The authors harness the generation capacities of each technology with a stochastic probability constraint as performed by [45]. The results show that they must increase the carbon price to at least 30 USD/tCO_2e from 2020 to 2050 from current levels (5 USD/tCO_2e). Another case is proposed by the authors in [46]. They used the ESM Long-range Energy Alternatives Planning System (LEAP) to propose other possible energy scenarios from current policies and their NDCs to meet the Chilean commitment. Their results show that transport, mining, and other industries require adequate renewable energy and energy efficiency policies to reduce emissions in the demand sectors (decarbonization). However, all the studies above that used ESM did not consider the nexus with other systems, such as water, agriculture, and land systems. The evaluation of nexus among these systems can be done using the GCAM-Chile study cited above as it endogenously considers the links across all these systems. A summary of the main aspects of some of these models and others is provided in Table 1.

Table 1: List of some Integrated Assessment Models and Energy System Models

Approach	Model	Coverage	Resolution	Institution(s)/Developed
IAM	GCAM [47]	Energy sector and links	5-year steps	Joint Global Change Research Institute
	ReMIND [29]	Energy sector and links	5 - 10 year steps	Potsdam Institut für Klimafolgenforschung
	IMAGE [48]	Energy sector and links	1- 5 year steps	Utrecht University, Netherlands PBL Netherlands Environmental Assessment Agency
	MESSAGE [49]	Energy sector	5-year steps	International Institute for Applied Systems Analysis
ESM	EnergyPlan [50]	Energy sector	Hourly	Sustainable Energy Planning Research Group
	TIMES [51]	Energy sector and links	Yearly	IEA-ETSAP
	ReEDS [52]	Power sector	Hourly	National Renewable Energy Laboratory
	LEAP [53]	Energy sector	Yearly	Stockholm Environment Institute
	Dispa-set [54]	Power and heat sectors	Hourly	Joint Research Centre, University of Liège , KU Leuven
	LEELO [43]	Energy sector	Hourly	Haas et al. (2018)
	PLEXOS [55]	Power sector	Hourly	Energy Exemplar
	OSeMOSYS [56]	Energy sector	Hourly	KTH-Royal Institute of Technology, University College London , Paul Scherrer Institute , World Bank (WB)
	H2RES [38]	Energy sector	Hourly	INTERENERGY

Based on the information presented above, this research represents the first attempt to evaluate how the introduction of hourly resolution (8760 time steps) affects the outcomes of the GCAM integrated assessment model (IAM). GCAM, as well as other IAMs, typically operate at a wider temporal granularity, overlooking hourly-level considerations such as resource availability and technical constraints within power plants, owing to their inherent complexity and the extensive range of systems they encompass. In essence, our reserach aims to quantify the impact of variability on the results generated by an integrated assessment model, with a specific focus on the Global Change Analysis Model (GCAM). To accomplish this, we use a soft-linking approach between the GCAM and the H2RES energy system models. This facilitates the complementary use of both models to address specific constraints considered by each model, which generates a greater benefit when evaluating decarbonization pathways. Previous studies have successfully employed a soft linkage to assess pathways. For instance, Fernandez-Vazquez et al. [57] established a soft-linking between OSeMOSYS and Dispa-Set. They evaluate alternative energy transition scenarios for Bolivia.

This research aims to evaluate the viability of alternative routes suggested by GCAM based on hydrological conditions and technology costs considering the endogenous links (nexus) among the five systems that GCAM addresses (holistic approach), within the context of an energy system model. To achieve this objective, GCAM results are evaluated with the H2RES energy system model, which considers high temporal resolution. This enables to conduct an hourly assessment of the potential impact of the energy system operation. This approach provides valuable insights into the feasibility of mitigation strategies and carbon neutral pathways that are obtained by GCAM, as it evaluates the role of hourly variations of renewable resources on those pathways defined by GCAM.

The rest of the paper is organized as follows. Section 2 describes the methodologies (GCAM-Chile, H2RES, and the proposed soft-link). Section 3 presents the case study and an overview of the scenarios. Subsequently, The results of our analysis and discussion, along with a comparative analysis, are presented in Section 4. Finally, Section 5 presents the conclusions of our research.

2. Method

This section presents the most important aspects of the GCAM-Chile and H2RES model. In addition, it shows how the integration of the two models is performed.

2.1. Overview of Global Change Analysis Model

The Global Change Analysis Model (GCAM) is an open-source integrated assessment model developed by the Pacific Northwest National Laboratory [58]. GCAM considers 32 geopolitical regions that contemplate the global interaction between the energy production and transformation sectors, such as economic, energy, agricultural, and land use. In addition, GCAM works with a five-year time step from 2015 (base year) to 2100 [59, 60]. Note that literature has shown success in studies linking GCAM to other models sector-specific models [61, 62]. Table 2 shows a summary of the data sources used by GCAM supply documentation [63]. Input parameters and other publicly available data can be obtained from `https://github.com/JGCRI/gcam-core/releases`.

Table 2: GCAM data. Source: [63]

Supply	Name	Source	Resolution
Energy	Historical supply of energy	IEA [64]	Specified by fuel, transformation sector, country, and year
	CO2 capture rates	Assumption	Specified by technology and year
	Retirement rules	Assumption	Specified by technology and year
	Logit exponents	Assumption	Specified by sector and subsector
	Share weight interpolation rules	Assumption	Specified by subsector and technology
	Cost of conversion technologies	Various	Specified by technology and year
	Capital cost	Annual Technology Baseline 2019	Specified by technology and year
	Fixed O&M costs	Annual Technology Baseline 2019	Specified by technology and year
	Variable O&M costs	Annual Technology Baseline 2019	Specified by technology and year
	Capacity factor	Assumption	Specified by technology and year
	Fixed charge rate	Assumption	Specified by technology
	Default efficiencies	Assumption	Specified by technology and year
	Default input-output coefficients	Assumption	Specified by technology and year
	Resource supply curves	Various	Specified by resource and year
	Historical non-CO2 emissions	CEDS [65]	Specified by country, technology, gas, and year
	CO2 emissions coefficients	CDIAC [66] and IEA [64]	Specified by fuel
	Historical CO2 emissions	CDIAC [66]	Specified by nation and year
Water	Surface water supply curves (cost and availability)	Xanthos output	Water basin and year
	Groundwater supply curves (cost and availability)	Turner et al. (2019) [67]	km3 available per USD
	Desalination cost	Global Constant	USD per km3
Food, feed, and forestry	Historical country-level production of crops	FAO	Specified by crop, country, and year
	Historical country-level harvested area for crops	FAO	Specified by crop, use, country, and year
	Historical sub-national production of crops	moirai [68]	Specified by crop, country and basin
	Historical sub-national harvested area of crops	moirai [68]	Specified by crop, country and basin
	Historical production of livestock	FAO	Specified by crop, use, country, and year
	Livestock feed coefficients	IMAGE,	Specified by commodity, feed system, IMAGE region and year
	Historical cost of production	USDA	Specified by crop, type of cost, and year
	Historical prices	FAO	Specified by country, commodity, and year
	Agriculture productivity growth	FAO	Specified by country, commodity, and year
	Logit exponents	Assumption	Specified by type of livestock
	Historical non-CO2 emissions	CEDS [65]	Specified by country, technology, gas, and year

GCAM uses the Shared Socioeconomic Pathway 2 (SSP2) scenario as baseline projections. In addition, GCAM has the possibility to use the other five shared socioeconomic pathways scenarios described in [69]. GCAM considers nine different primary resources (fuels) characterized as renewable or non-renewable in the energy sector. These resources are modeled through exogenous supply curves. In addition, these fuels have different efficiencies and specific costs from the energy transformation sector. Finally, the end-use sectors are the ones that consume these fuels, which are distributed as the transportation sector, which is divided into passenger and freight, including road, rail, air, and shipping; the building sector, which is divided into residential and commercial and, finally, the industry sector which is divided into iron & steel, cement, chemicals, fertilizer, aluminum, construction, mining energy use, agricultural energy use, and other industry [70].

$$C = t + \underbrace{\sum_{j=1}^{n} i_j}_{\text{Cost of input}} + \overbrace{\sum_{k=1}^{m} g_k}^{\text{GHG value}} - \underbrace{\sum_{l=1}^{o} v_l}_{\text{Secondary output}} \tag{1}$$

The Equation (1) represents the total cost for a technology. The parameter C is the total cost, and t represents the exogenously fix technology cost, such as maintenance costs. In addition, i_j represents the variable (fuel cost) cost of input j, and g_k is the GHG value of gas k, which represents the cost associated to the emissions produced by gas k (emissions levels times the emissions cost). Finally, v_l is the value of secondary output l [71].

$$s_i = \frac{\alpha_i\, c_i^{\gamma}}{\sum_{j=1}^{N} \alpha_j\, c_j^{\gamma}} \tag{2}$$

Regarding participation by technology, Equation (2) represents the share for each option of the decision-making process, known as a Logit-based choice model. This equation shows that the priority or share of a technology is established by its costs or profits [71]. The logit coefficient γ is exogenously defined and shows to what extent the share of each technology is affected by its cost or benefit [70]. In equation (2), α_i is the share-weight of technology i, c_i is the cost of technology i, and γ is the logit exponent.

Finally, GCAM projects emissions of a suite of GHGs and air pollutants, including CO_2 and non-CO_2 emissions (such as N_2O, CF_4, NO_x, NH3 or CH_4, among others), and they are determined by the evolution of the demand sectors, and combination of technologies [72]. on the one hand, the non-CO_2 emissions are loaded from the Community Emissions Data System (CEDS) inventory [73].

$$E_t = A_t \times F_{t0} \times (1 - MAC(Eprice_t)) \tag{3}$$

On the other hand, the CO_2 emissions come from global emissions by fuel from the Carbon Dioxide Information Analysis Center (CDIAC) global inventory [74]. Non-CO_2 emissions levels for future periods are determined by Equation (3). The emission level E_t depends on the emissions factor F_{t0}, A_t is the activity level, MAC is the Marginal Abatement Cost curve, and $Eprice_t$ is the emissions price [72].

2.1.1. GCAM by incorporating country-level representation in Chile

GCAM-Chile was constructed from the base version of GCAM v6.0, where Latin America is represented by Colombia, Argentina, and Brazil as independent energy-economy regions, and two aggregate regions: South America Northern (French Guiana, Guyana, Suriname, Venezuela) and South America Southern (Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay). Therefore, to conduct this research, an additional disaggregation was made. Specifically, Chile was separated from the South America Southern region, now encompassing 33 energy and macroeconomic regions. This process followed the method outlined in [75], which was used to develop other regional versions of GCAM, such as GCAM-USA [76], and GCAM-Korea [77]. This method modifies the raw input files that define the regional structure of GCAM through an R package developed by Khan et al. [78]. Therefore, the disaggregation that was developed adds a new energy-economy region to the model, and assigns the corresponding existing water basins and land regions to the new energy-economy region, in this case, Chile. GCAM-Chile can assess multi-sectoral energy supply and demand, along with resultant emissions, within a cohesive energy, economic, and climate modeling framework. The energy module in GCAM-Chile was calibrated utilizing Energy Balances by IEA data [64], with 2015 established as the base year (GCAM v6.0). Specifically for the electricity sector, data from Chile's 2019 energy balance was used to calibrate the electricity generation in 2020 [79], also, the calibration considered the low tech cost by PELP [80]. For the economic sector, PELP population and GDP data were employed for calibrating official data for Chile [80].

2.2. *Overview of Highway to Renewable Energy Systems model*

The Highway to Renewable Energy Systems (H2RES) model consists of three main modules [81]. The first one represents generation and flexibility options; this module considers two types of power plant units. On the one hand, the non-dispatchable units whose input are renewable resources, including hydro (Run of the river hydro (HROR)), solar, and wind. On the other hand, the dispatchable units are those whose primary fuel consumption input considers coal, oil/diesel, natural gas, biomass, nuclear, and hydro units. H2RES model considers hydro in the specific form of Hydro-dam (HDAM) and hydro-pump Hydro-pump (HPHS); both hydro technologies have storage capacity. The model optimizes long-term planning, i.e., the capacity investments for each technology and year of the planning horizon while assuring that a set operational, technical, and policy constraints, such as limits on CEEP, CO_2 Emissions, or Renewable Energy Penetration Standards (RPS), are met. Also, the H2RES model considers heat generation supplied by different technologies such as gas and biomass (traditional boilers), electric heating (heat-pumps and electric boilers), and CHP units. These heat units must meet the demand in both general demand sectors and district heating areas [38, 81] (See Figure 1).

The second module in the H2RES model is the transformation sector, including Hydrogen (Power-To-H2), heat (Power-To-Heat), and fuel cells (Power-To-Power). In addition, H2RES considers storage for different energy carriers, such as hydrogen storage, hydro storage, heat storage, and EV storage. Finally, the last module represents the final demand sector: transport, buildings, commercial, and industry.

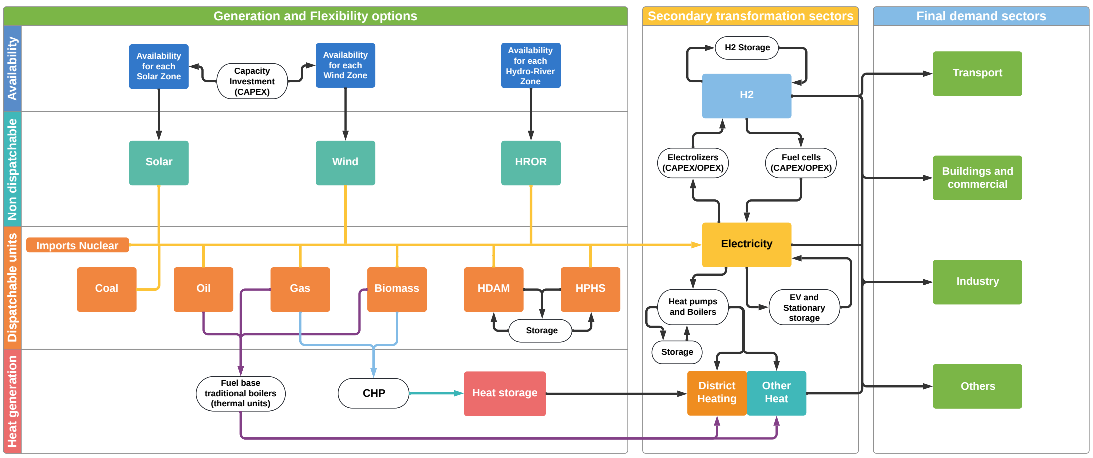


Figure 1: Modules H2RES model and framework. Source: [38]

$$\sum_{y}\sum_{p}\sum_{t} df_y \Big(\underbrace{C_{t,p,y}\, D_{t,p,y}}_{(1)} + \underbrace{TC_{t,y}\, K_t\, Inv_{t,y}}_{(2)} + \underbrace{R_{t,p,y}\, Ramp_{t,p,y}}_{(3)} + \underbrace{I_{p,t}\, Inp_{p,y}}_{(4)} + \underbrace{CO2Price_y\, CO2Level_{t,p,y}}_{(5)} \Big) \qquad (4)$$

The overall objective of the H2RES model is to minimize the total annualized operational and capacity investment cost over the planning horizon. The total cost is separated into five general terms, as shown in Equation 4. The first term of the equation represents the fuel and non-fuel costs that are related to the dispatch of technology t in period p for each year y. The second term represents the capital investment costs. In addition, the third term represents operational ramps (up and down) costs for each technology t in period p for each year y. Finally, the fourth term represents the import cost per period p, and for each year y, the fifth term of the equation represents the cost of CO_2 emissions for each technology t in period p, and for each year y.

To calibrate H2RES, we utilized 2020 as the base year, and the installed capacity was extracted from the 2020 energy report obtained from [79]. Additionally, the renewable ninja simulator [82] was used to acquire three profiles of solar and wind generators in Chile. Similarly, the distribution of electricity demand was derived from Energía Abierta [83], using 2019 as the base year within an hourly time horizon.

2.3. *Coupling of the Global Change Analysis Model for Chile with the Highway to Renewable Energy Systems model*

Results from GCAM-Chile, particularly those pertaining to investment of technologies in the power sector and demand levels (power and heat), are passed to H2RES in the same way as the exogenous parameters considered in the GCAM-Chile. These parameters include technological costs, fuel prices, and installed capacity from the Chilean reports of 2015 [84] and 2020 [79]. These results and parameters are used to assess the operational feasibility of the proposed investment plans as well as the required level of flexibility needed to ensure balancing of supply and demand. Note that the proposed methodology can be generalized to any region of interest in GCAM. Also, GCAM-Chile provides decarbonization pathways in an integrated regional framework, i.e., accounting for the demand and supply levels of all regions considered in GCAM. Also, this research imposed carbon neutrality conditions on the Chilean region within GCAM-Chile (policies). For the remaining GCAM regions, a global pathways to net zero emissions in 2050 was imposed in order to guarantee consistency in the model. To establish a coupling between the two models, different hourly distributions are employed. Firstly, an hourly distribution of electricity demand is developed using official profiles from the Government of Chile (Energía Abierta) [83]. Similarly, the hourly distribution of heating demand presented by Paardekooper et al. is utilized [85]. For hydrogen demand, an hourly distribution presented in [38], calibrated based on data from the Chilean case, is employed. Lastly, the coupling incorporates the hourly distribution of renewable resources for five representative solar-PV zones and five representative wind zones in Chile. The zonal profiles were obtained from the Renewable Ninja simulator [82].

Figure 2 shows a general framework for integrating the GCAM-Chile and the H2RES model. Inputs in GCAM-Chile include the carbon budget, biomass ceiling, mitigation strategy, and water restriction (hydrological projections) in electricity generation with Hydro technology. The additional capacity and retirements of the power plants and demand levels (power and heat) due to the transition in the energy and non-energy sectors are used as inputs by H2RES.

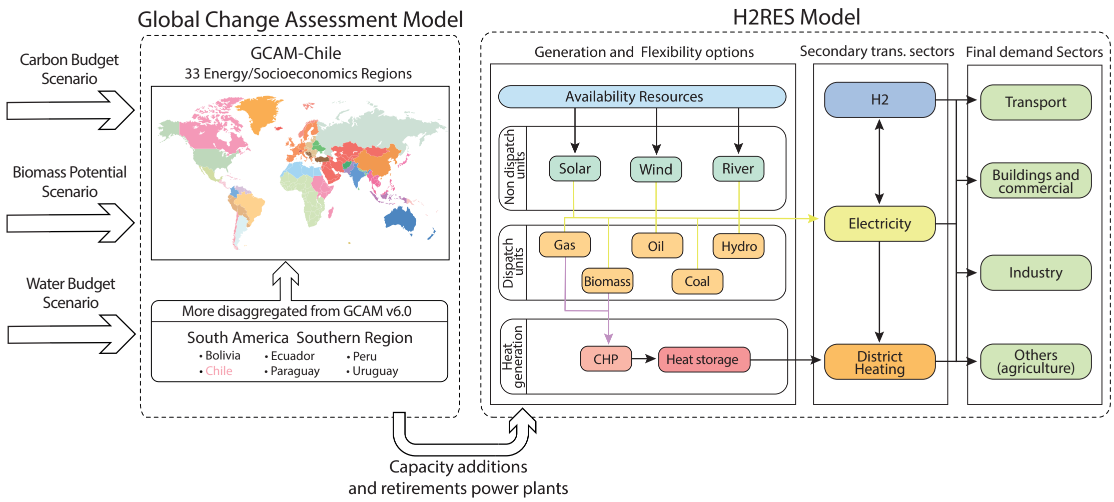


Figure 2: GCAM-Chile and H2RES model integration general framework

3. Case study: The Chilean energy

This section introduces the case study, providing essential elements and contextualizing the current Chilean scenario. In terms of emissions, 77.4% of the total GHG emissions are generated in the energy sector, making it the leading polluter. Such high emissions share are due to the production of electricity, accounting for approximately 38%, whose primary input fuels are coal and natural gas. The second GHG emitter corresponds to the transport sector, which represents 32% of the total emissions [86]. To further accelerate the decarbonization in the power sector, in 2020, Chile updated its NDC proposing that 70% of electricity production should come from renewable energy by 2050 (Wind, solar, geothermal, biomass, and mini-hydro), while coal-based power plants should be phased out by 2040. However, Chile is currently in the process of evaluating the possibility of anticipating the phase-out date of coal plants to 2030 [87].

In Chile, The transportation and industry sectors are the primary consumers of Liquids. The transportation sector in 2019 had a share of almost 70% of the total Liquid consumption, similar to 2015. The industry sector consumed nearly 26% of the total Liquids, facing a slight decrease from 2015 (28%) [88]. The final energy consumption in Chile depends heavily on coal, liquids, and gas, representing 80% in 2019. The vast majority are Liquids which represent almost 50% of the total. In contrast, Biomass and electricity have a share of 21% and 13%, respectively, despite Chile's strategies to promote renewable energy use [88].

Figure 3 shows in the left panel the installed capacity in the years 2010 to 2020, where an increase in the renewable installed capacity of 804% in 2015 and 3005% in 2020 compared to the year 2010 can be observed. This increase is due to the installation of solar technology going from almost negligible capacity in 2010 to 3248.4 MW in 2020. In addition, there is an increase in the installed capacity of wind technology of 465% in 2015 and 1145% in 2020 when compared to 2010 [79, 84]. On the other hand, the right side of Figure 3 shows electricity generation between 2010 and 2020. It is important to note that in 2010 hydro generation was almost 38% of the total yearly generation. The share of renewable electricity generation increased, reaching 45% in 2020 despite an increase in total electricity generation of 26% in 2015 and 35% in 2020 compared to 2010 [79, 84].

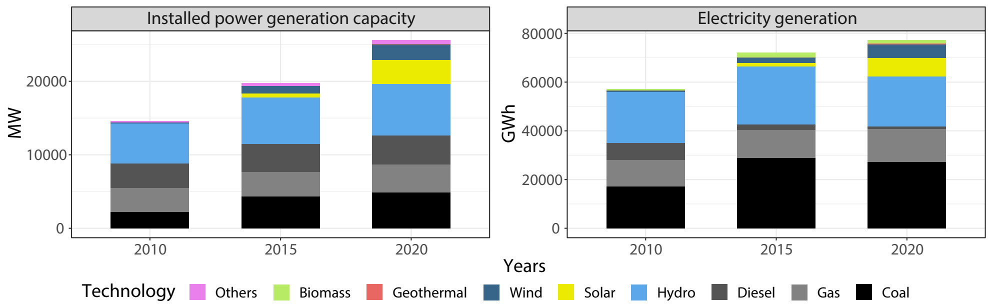


Figure 3: Installed power capacity and electricity generation by technology

The increase in installed renewable capacity is a result of the prominent energy potential given by the geography of Chile. The north of Chile has a vast potential for solar energy and Concentrated Solar Power (CSP potential in the Arica and Parinacota region to the Atacama region). In the south, there is a significant potential for wind energy and hydropower [80, 89] (For more details, see Figure 4). The total renewable energy potential is 40.452 MW for wind energy, 2.192.999 MW for solar (1.640.128 for the PV case and 552.871 MW for the solar CSP case), and 12.472 MW for hydro energy [89, 90].

Regarding Heating in Chile, in [85], the authors create a Roadmap to show the future of the sector and its role in the Chilean energy system. This is because the demand for heat is covered mainly by individual heating technologies, which are usually fueled by biomass (southern regions of Chile). These technologies could be more polluting and inefficient [91]. The residential sector consumed 50,763 GWh in 2018. The primary energy consumption was firewood, covering 39.6%. The second majority belongs to gas consumption at 31.4%, then electricity follows with 25.7%, and the rest was paraffin and pellets (3.3%) [92]. Recently, the decontamination of the heating sector has been addressed. Authors in [91] show that the Chilean decarbonization and decontamination plan is consistent with the goal of near 100% renewable energy systems. For example, 57% of households (70% apartments) should be heated

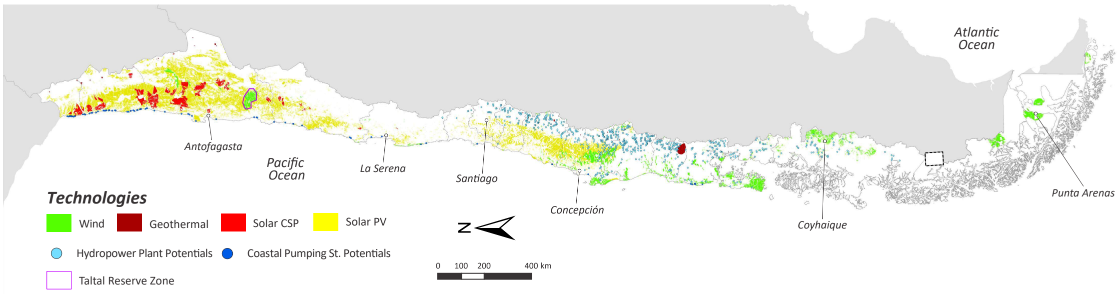


Figure 4: Renewable Energy Potentials by Long-Term Energy Planning. Source: [80]

with electricity by 2050 or commercial electric public heating by 2050; these actions were declared a target in the Chilean NDC [93].

3.1. Scenario development

Chile aims to achieve carbon neutrality by 2050, with an emissions peak by 2025. Additionally, Chile has committed to phasing out all coal power plants and replacing them with renewable energy by 2040. Note that none of the scenarios studied in the Chilean PELP [80] observe CCS among new technologies that are deployed in the power sector towards 2050. Therefore, scenarios used in this research do not consider CCS technology as a viable one. Additionally, Chile encourages sustainable building such as public and commercial electric heating, industry, and e-mobility by 2035, 2040, and 2050, such as public transportation [93]. Similarly, in e-mobility, the reduction in the use of fossil fuels in passenger vehicles was modeled by increasing the use of electric cars (BEV, FCEV). In addition, in freight transportation, there was an increase in the use of hydrogen and electricity to provide to this sector. Lastly, in the mobile mining industry, the utilization of electricity and hydrogen shown an increase, with the consideration of a 10% reduction in technologies between 2025 and 2030, along with an additional 3% reduction in the subsequent years. On the other hand, the hydrogen strategy was modeled considering a cost reduction of electrolyzers for each wind and solar energy sector. This cost reduction drives the use of hydrogen in energy end-use, especially in transport and industry. In the building policy, the focus was on residence heating, promoting the use of electricity, and reducing the reliance on liquids and biomass. Also, in the Planificación Energética de Largo Plazo (PELP, long-term energy planning), a dry hydrological scenario is assumed due to the recent conditions (one of the driest on record) for the projection of electricity [80]. To model the hydro trajectories in the electricity sector across various carbon-neutral scenarios, hydro generation is incorporated as a parameter in GCAM from [80, 94]. This incorporation results in two scenarios: Dry and Normal hydrology.

This research designed seven scenarios to evaluate the above. The first scenario is Business As Usual (BAU), which represents the Chilean evolution without restrictive policies, new building efficiency standards, or e-mobility targets. The second scenario considers a peak of emissions in 2020 and a target of 65 $MtCO_2e$ of emissions (economy-wide CO_2 constraints) in 2050, a coal phase-out in 2030 with dry hydrology (hydro-based generation), without consideration of the CCS technologies implemented. The third scenario considers a peak of emissions in 2020 and a target of 65 $MtCO_2e$ of emissions (economy-wide CO_2 constraints) in 2050, a coal phase-out in 2030 with normal hydrology without consideration of the CCS technologies implemented. The fourth and fifth scenarios vary in one aspect of the phase-out of the coal plants as stipulated in the Chilean NDC, i.e., coal phase-out by 2040 (they still consider the option of dry and normal hydrology). all NDC scenarios have the consideration of economy-wide CO_2 constraints (budget). In addition, all scenarios consider all the GHG emissions that Chile declares in its NDC, such as CO_2, Methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF6), and Nitrogen Trifluoride (NF_3) gases [93]. Note that the CO_2e limits modeled in this research are economy-wide constraints, hence, directly affecting emissions produced by the energy and non-energy systems modeled in GCAM-Chile. Therefore, decarbonization pathways are based on changes depending on the nexus among energy and non-energy system (e.g., water and land systems). Additionally, all NDC scenarios considering the electromobility [95], and hydrogen strategy [96] to represent Chile's long-term planning in greater detail.

In summary, for Chile, this study considers seven scenarios (Business As Usual and all mitigation scenarios) that share the same socioeconomic growth trajectory based on a middle-of-the-road socioeconomic pathway (SSP2), taking into account the climate targets 4p5. To incentivize the transition to renewable energies, the costs of low technologies according to PELP were used. Additionally, two types of coal phase-out and hydrological are considered, respectively. The first one contemplates the NDC on the phase-out of coal plants by 2040, and the second one considers the accelerated phase-out by 2030. This also takes into consideration two types of hydrology in the dry and Normal electricity sectors. Similarly, the rest of the regions considered by GCAM use the default technology costs, considering the socioeconomic growth trajectory based on a middle-of-the-road socioeconomic pathway (SSP2), and also taking into account the climate targets 4p5. Finally, the rest of the regions as a whole reach zero emissions by 2050, considering economy-wide CO_2 constraints (CO_2 and non-CO_2 gases). The overview of the scenarios analyzed in this study is presented below in Table 3.

Table 3: Overview of scenarios

Name scenario	**Emissions peak**	**Coal phase-out**	**Hydrology type**	**Buildings policy**	**Hydrogen policy**	**e-mobility policy**	**Technology cost**
Business As Usual	-	-	Dry	-	-	-	Ref
NDC_NoCoal2030_D	2020	2030	Dry	✓	✓	✓	Low
NDC_NoCoal2030_N	2020	2030	Normal	✓	✓	✓	Low
NDC_NoCoal2040_D	2020	2040	Dry	✓	✓	✓	Low
NDC_NoCoal2040_N	2020	2040	Normal	✓	✓	✓	Low
NDC_NoCoal2040_RCost_D	2020	2040	Dry	✓	✓	✓	Ref
NDC_NoCoal2040_RCost_N	2020	2040	Normal	✓	✓	✓	Ref

The budget and emissions of the BAU scenario and the projected emissions of the six NDC scenarios are shown in Figure 5. Additionally, Figure 5 illustrates the 2050 emissions target proposed by the PELP [80]. It highlights that emissions in 2050 are projected to be 65 $MTCO_2e$, with the expectation that the forestry sector and land use will absorb these emissions. This assumption is considered in this study. The BAU scenario increases from 120.32 $MTCO_2e$ in 2020 to 137.72 in 2050, representing an increase of 14.47%, which is generated by the rise in fossil fuel technologies. On the other hand, the NDC scenarios have peak emissions in 2020, which is 120.32 $MTCO_2e$, reducing their emissions to 65 $MTCO_2e$ in 2050, representing a decrease of 45.86% between 2020 and 2050 (NDC scenario). Furthermore, the reduction in the year 2050 between the BAU and NDC scenario is 52.81%. Finally, the emissions budget of the NDC scenarios is based on the goals proposed in [93]. The intermediate goal of 90 $MTCO_2e$ emissions in 2030 and emissions by 2050 of 65 $MTCO_2e$ are highlighted.

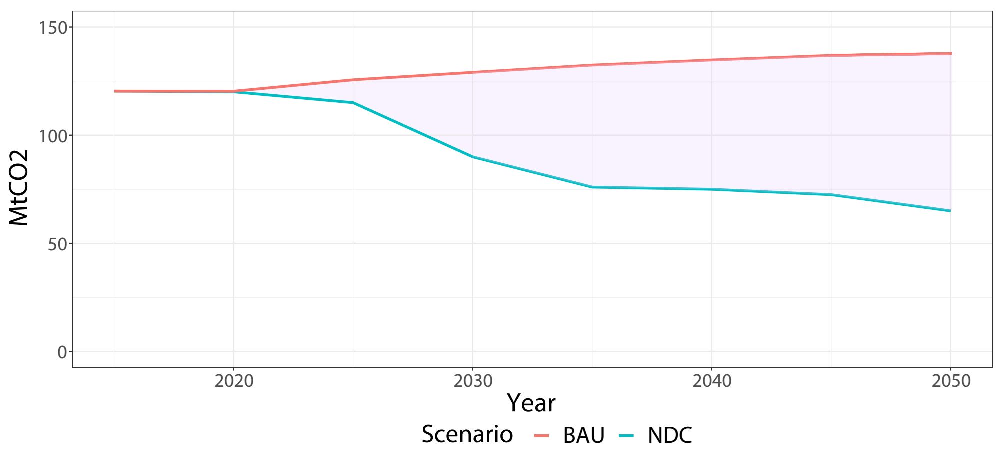


Figure 5: Carbon budget

3.1.1. Calibration

As stated earlier in this paper, the proposed disaggregation in GCAM allows for a detailed study of the Chile region and the evaluation of how the introduction of hourly resolution affects its outcomes. This study analyzes seven scenarios to identify energy transition pathways aligned with the most relevant Chilean targets. GCAM-Chile is executed over a time horizon of 35 years, with 2015 as the base year. It enables the projection of transformations in the energy sector for each scenario. Furthermore, these scenarios are analyzed in the H2RES model to explore the operational viability of the results from the energy pathways provided by GCAM-Chile. Figure 6 reveals the calibration and results generated by GCAM-Chile and H2RES compared with the official data for 2015 and 2020 obtained from [79, 84]. To implement the calibration for 2020, the share weight linked to each electricity sector is adjusted under an error threshold of 5% for 2015 in GCAM and 10% for 2020 in both models. On the other hand, the technology costs in both models were adjusted according to PELP [80] and its average annual profile for GCAM, and the hourly profile for H2RES in renewable technologies by [82].

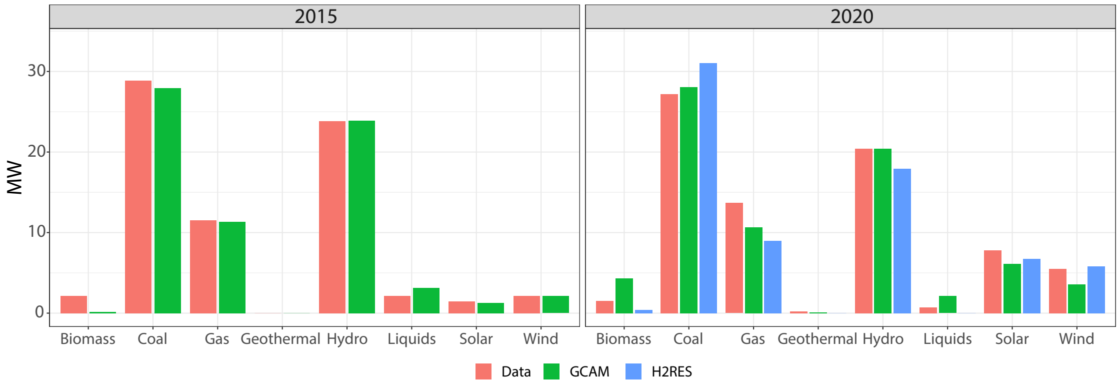


Figure 6: Data, GCAM and H2RES calibration.

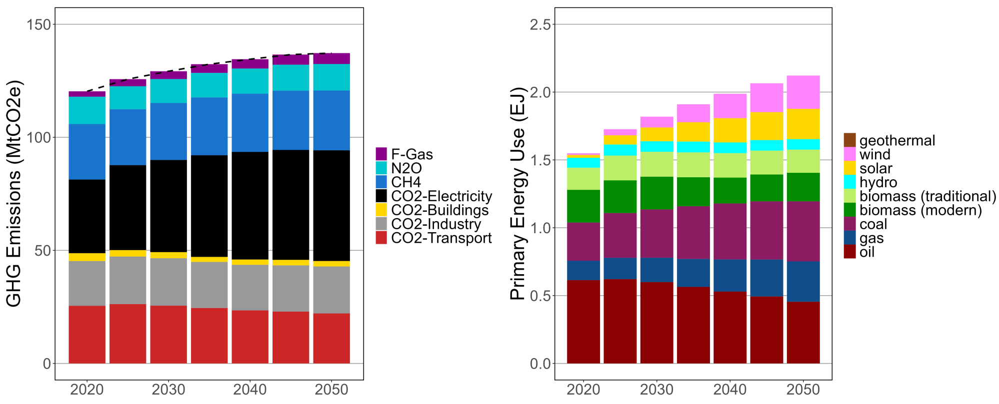
4. Results

This section presents and analyzes the results of the GCAM model, the soft-link between GCAM and H2RES, and, finally, a discussion of the results in the literature.

4.1. Business as usual scenario analysis and projections based on GCAM-Chile

First, the scenario analysis based on GCAM-Chile is introduced. Figure 7a shows the GHG by sector from 2020 to 2050 projected by GCAM-Chile for the BAU case. As stated in the previous section, the Energy sector is the main responsible for GHG emissions, with the power and transport sectors being the two largest individual emitting sectors in 2020. Under current conditions, by 2050, the power sector is projected to be the main GHG emitting sector, driven by the use of fossil fuel plants needed to supply an increased demand (see Figure 8 below). The transport sector is expected to slightly reduce the level of emissions while the building sectors do not show significant differences. Figure 7b shows the primary energy use for the BAU. Note that the oil (and derivatives) level has an important drop towards 2050, a result that can be linked to the reduced GHG level from the transport sector observed in Figure 7a.

Regarding Chile's electricity sector, generation in 2020 reached 75.41 TWh, and it is projected to increase 199.35% by 2050 (225.73 TWh), with a share of renewable energy going from 45.86% in 2020 to 68.37% by 2050 (Considering Hydro, Geothermal, Biomass, Solar and Wind technologies). Figure 8 (left panel) shows the increase in electricity generation by fuel for the BAU scenario. It can be seen that fossil technologies continue to contribute an average of 54.14% in 2020, decreasing their share to 31.63% without giving access to a higher share of renewable sources. In addition, the right panel of Figure 8 shows the contribution (percentage) of electricity participation in heating demand (space heating and hot water for residential and commercial sectors), growing from 21.6% in 2020 to 52.3% in 2050.



(a) GHG by Sector

(b) Primary energy use

Figure 7: Information about BAU scenario

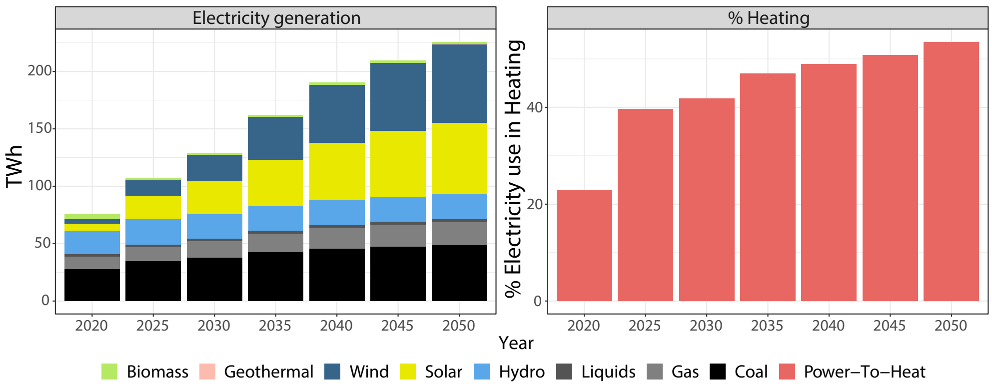


Figure 8: Electricity generation by technology and Power-To-Heat from 2020 to 2050 in BAU scenario

4.2. Analysis of scenarios with politics in GCAM-Chile

Figure 9 shows the GCAM-Chile result, focusing on electricity generation by fuel source for all six policy scenarios. Results indicate that electricity generation in all policy scenarios is larger than the case of the BAU scenario. This indicates that in order to reach carbon neutrality by 2050, there must be a significant deployment of power generation capacity, particularly from renewable sources, needed to achieve electrification of demand sectors and sector coupling. Note that coal-based generation is phased out by 2030 in NDC_NoCoal2030_D, and NDC_NoCoal2030_N. Similarly, the NDC_NoCoal2040_D, and NDC_NoCoal2040_N scenarios phase out coal by 2040. However, when a comparison across the policy scenarios is done, it is also possible to note that the NDC scenarios with dry hydrology (NDC_NoCoal2030_D, and NDC_NoCoal2040_D) also have more electricity generation, particularly from solar (8%) and wind (10%) sources. This increase is due to the type of hydrology. There is a decrease of almost 40% in electricity generation with hydro technology; consequently, renewable resources must cover this demand. Therefore, when NDC scenarios are considered, alternative decarbonization pathways are obtained by GCAM-Chile, introducing important investments in renewable generation and electrification of end-use sectors, such as residential and commercial space heating.

Table 4 summarizes the percentage contribution of solar and wind technologies to electricity generation and total renewable energy that considers Biomass, Geothermal, Hydro, Solar, and Wind. Fossil fuels, mainly gas-fired plants, supply the remainder of electricity generation. It is not considered coal due to the phase-out of this technology in 2030 or 2040. Also note that, for instance, the NDC_NoCoal2040_D scenario is almost entirely renewable, as approximately only 4.84% of the electricity generation comes from gas-fired plants.

In terms of investment, when scenarios in terms of similar hydrology are compared, considering the accelerated

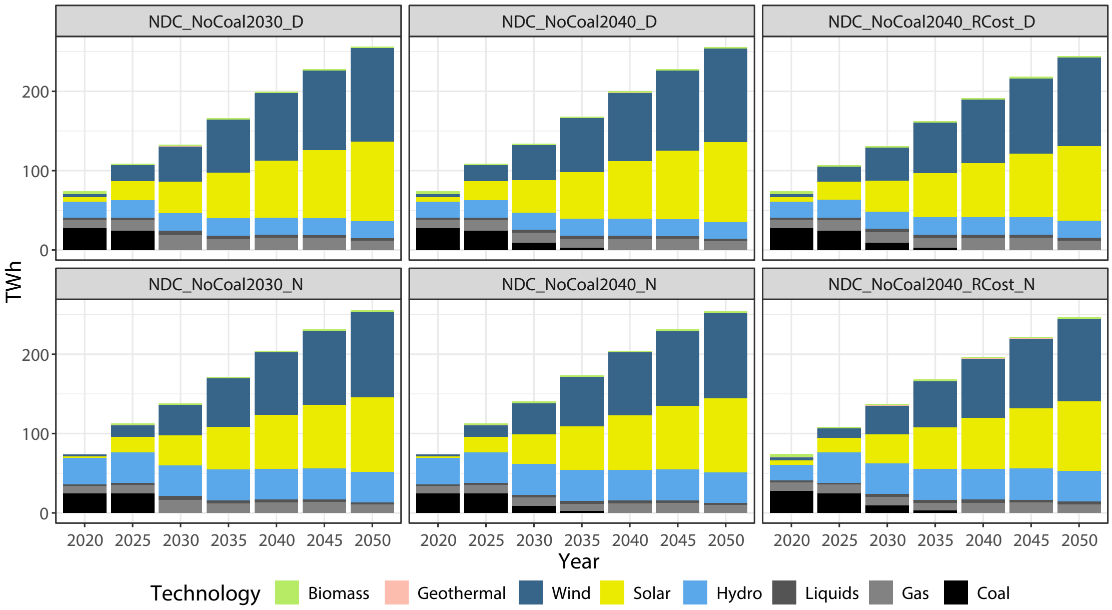


Figure 9: Electricity generation by technology from 2020 to 2050 in policy scenarios

Table 4: Percentage of renewable generation in GCAM-Chile

Scenarios	Electricity						
	2020 (TWh)	2050 (TWh)	Investment Wind (GW)	Wind % (2050)	Investment solar (GW)	Solar % (2050)	Total renewable (2050)
BAU	75.41	225.73	15.11	30.22	22.29	27.69	68.37%
NDC_NoCoal2030_D	74.29	256.42	22.02	45.80	29.63	39.15	94.16%
NDC_NoCoal2030_N	73.36	255.14	24.00	42.07	32.30	36.62	94.73%
NDC_NoCoal2040_D	74.29	255.74	24.19	45.99	32.29	39.30	94.53%
NDC_NoCoal2040_N	73.36	253.97	26.42	42.27	34.96	36.78	95.16%
NDC_NoCoal2040_RCost_D	74.29	244.23	23.38	45.51	31.73	38.42	93.61%
NDC_NoCoal2040_RCost_N	73.36	246.78	22.63	42.00	30.68	35.68	94.26%

retirement of coal plants, there is a difference of 1% in total investment. However, when different hydrologies are compared, for the same scenario of phase-out coal plants, there is a difference of almost 10% in total investment. This difference is because the hydro generation increase leads to lower renewable technology investment. Although the total investments of the technologies are similar when comparing scenarios with similar hydrology and different phase-out scenarios, the distribution is different. For example, when analyzing the RE_NoCoal2040_D scenario, the investments are constant and smooth due to the phasing out of coal plants. In contrast, when comparing the RE_NoCoal2030_D scenario, the investment in gas technology is approximately 34% in 2030. This significant investment is because gas replaces coal generation. Figure 13 shows the annual investment where it can be seen that in the coal phase-out 2030 scenarios, there is a higher investment in gas technology of approximately 80% compared to the coal phase-out 2040 scenarios.

The degree of electrification of demand sectors, as well as the share of other fuels, is shown in Figure 10. It can be noted that the share of electricity towards 2050 increases in all scenarios and all sectors. The Buildings sector reach an electrification level of about 55%, the industry sector of 80%, and transport sector close to 45%. The transport sector also shows an important use of Hydrogen, which helps to reduce the level of liquids. On the other hand, biomass is used alongside electricity in industry and buildings to get rid of liquids, gas, and coal usage. Considering the results, it can be noted that after the decarbonization of the power sector, the largest share of fossil fuels remains in the transport sector, being the hardest to decarbonize fully.

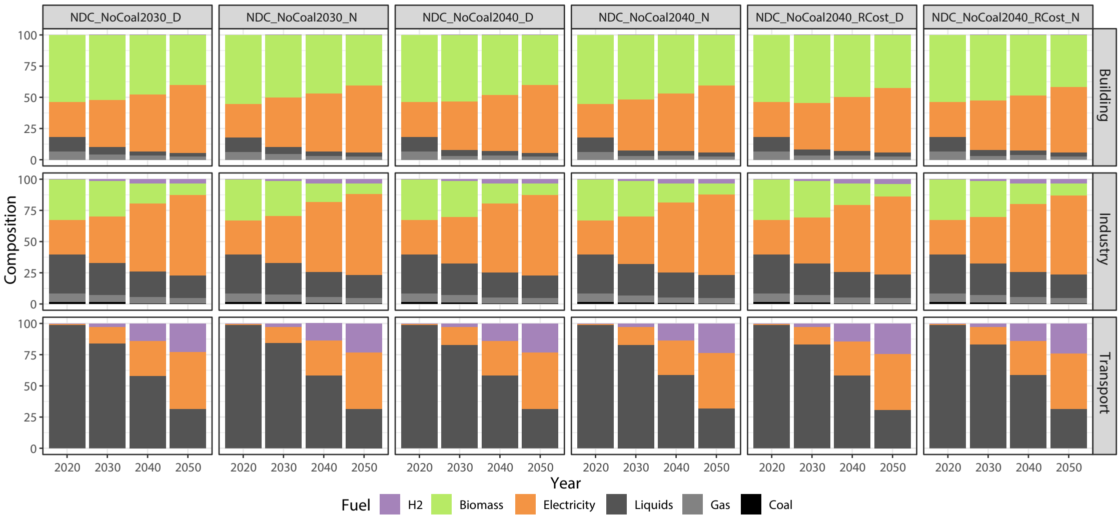
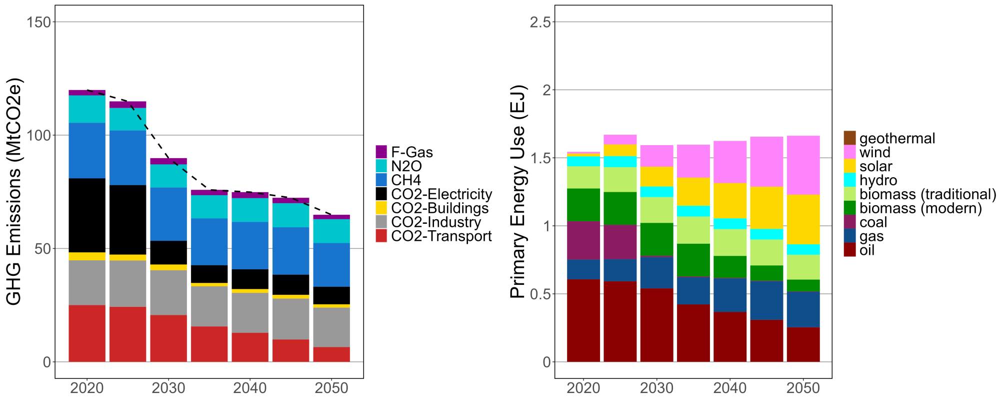


Figure 10: Final use demand by fuel share in all scenarios with policy

In terms of emissions and primary energy use (see Figure 11), when comparing, for instance, the BAU scenario to the NDC_NoCoal2030_D scenario, there is a decrease in fossil fuels use of 44% for Oil, 12% for gas, and 99% for coal by 2050. In the case of renewable energy use, there is an increase of 77% for wind and 63% for solar energy use. Reduction of fossil fuels and increased renewable energy use translate to significant emissions reductions (see Figure 11a). Emissions reductions come primarily from the power sector (coal phase-out policies as well as increased renewable electricity) as well as from the transport sector. The power sector reduces emissions by 84% while transport has a 71% reduction. Finally, in the buildings and the industry sectors, a lower reduction of emissions is reflected, accounting for 38% and 16%, respectively. Similar results are obtained for the rest of the scenarios.



(a) GHG by Sector

(b) Primary energy use

Figure 11: Primary energy use and GHG emissions for NDC_NoCoal2030_D scenario

Results also indicate that an accelerated phase-out of coal-based power plants would have a higher economic impact in Chile's energy future. Accelerated phase-out of coal-based technology increases costs by 0.3 billion 2010 USD on average. In normal hydrology scenarios (NDC_NoCoal2030_N and NDC_NoCoal2040_N), the average cost between 2021 and 2050 is expected to be USD 120.4 billion 2010 USD. However, during dry hydrology scenarios (NDC_NoCoal2030_D and NDC_NoCoal2040_D), the investment cost increases by approximately 6% in the same period. This increase means that dry hydrology scenarios are expected to generate an average cost of USD 127.1 billion 2010 USD. Figure 12 illustrates each scenario's capital investment for electricity generation capacity.

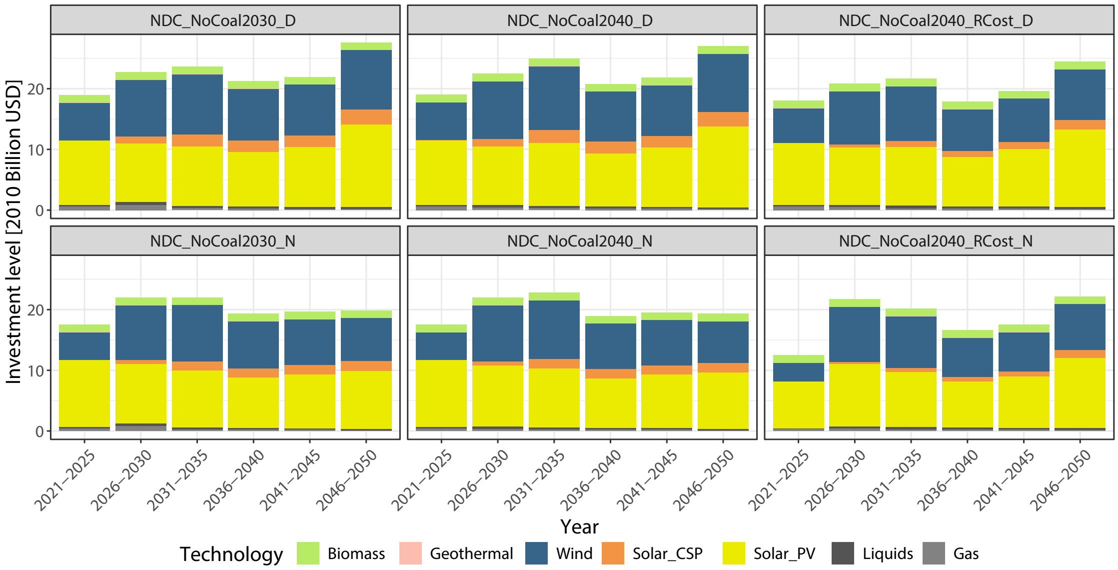


Figure 12: investment for electricity generation for NDC scenarios from 2021 to 2050.

4.3. Scenario Analysis with H2RES - Soft linking approach for hourly analysis of carbon neutrality scenarios

As mentioned earlier, GCAM-Chile, although it can integrate energy and non-energy systems, it does not correctly account for the hourly variability of renewable sources as it considers an average capacity factor. Therefore, it might provide projections that are not feasible when no flexibility options are fully available. To evaluate this, this paper assesses the conditions under which GCAM-Chile results are feasible when hourly profiles of renewable energy sources are considered. To do so, H2RES is fitted with data (results) regarding investment plans (capacity additions and demand levels) and the demand for power and heat from GCAM-Chile. Then, an assessment regarding the feasibility of the investment plans is carried out, and if not, required levels of flexibility options needed to balance supply and demand at an hourly scale are obtained. The investments that are passed to H2RES are shown in Figure 13.

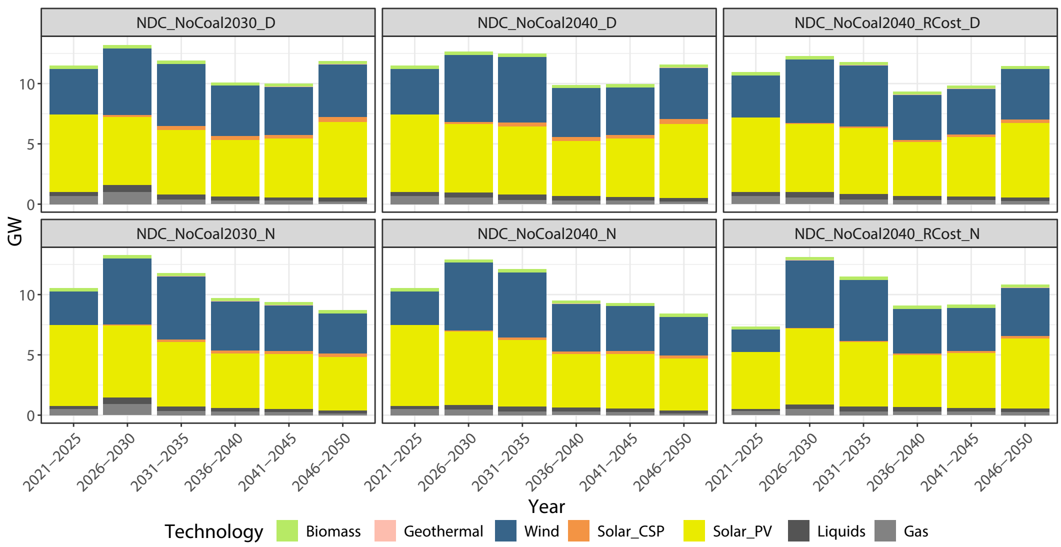


Figure 13: Investment by technology from 2025 to 2050 in the NDC scenario by GCAM

In terms of electricity generation, Figure 14 shows the hourly electricity generation levels obtained from the soft link between H2RES and GCAM-Chile in BAU scenario for 2020. It can be observed that there is an increase in fossil and hydro generation during the autumn and winter seasons, which are the seasons of lower temperatures in Chile. The increase is driven by the lower availability factor of solar energy and increased heat demand.

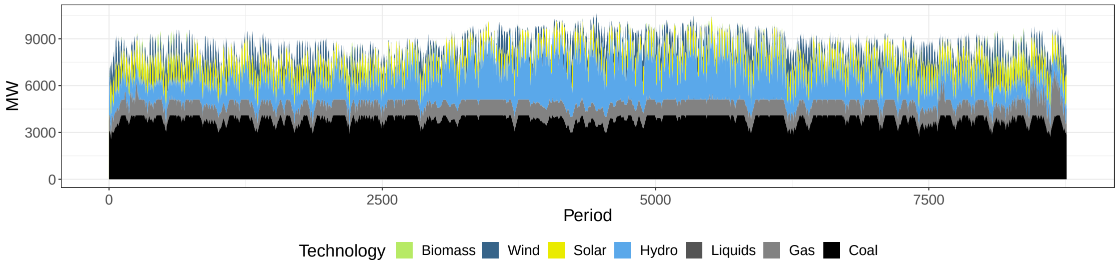


Figure 14: Electricity generation by technology in 2020 in BAU scenario

Figure 15 shows, for each scenario, the generation for each technology per year. The first observation is that H2RES shows a higher level of electricity generation compared to results from GCAM. This result is driven mainly by two factors. First, the fact that H2RES considers an availability profile (0 - 1) instead of an average capacity factor results in a peak-hour generation that might result in curtailment or excess electricity generation. Secondly, since there is an hourly variability of wind, solar, and hydro-river sources, H2RES requires larger levels of generation from fossil plants (natural gas and liquids) in order to handle such variability and to match demand and supply at every hour. The degree of excess electricity (CEEP) due to the renewable energy variability is shown in Table 5. It can be noted that the CEEP level in 2050 ranges between 17% to 20% in the NDC scenarios. If the CEEP level is deducted from the H2RES results, it is observed that generation levels in H2RES are indeed similar to those predicted by GCAM-Chile.

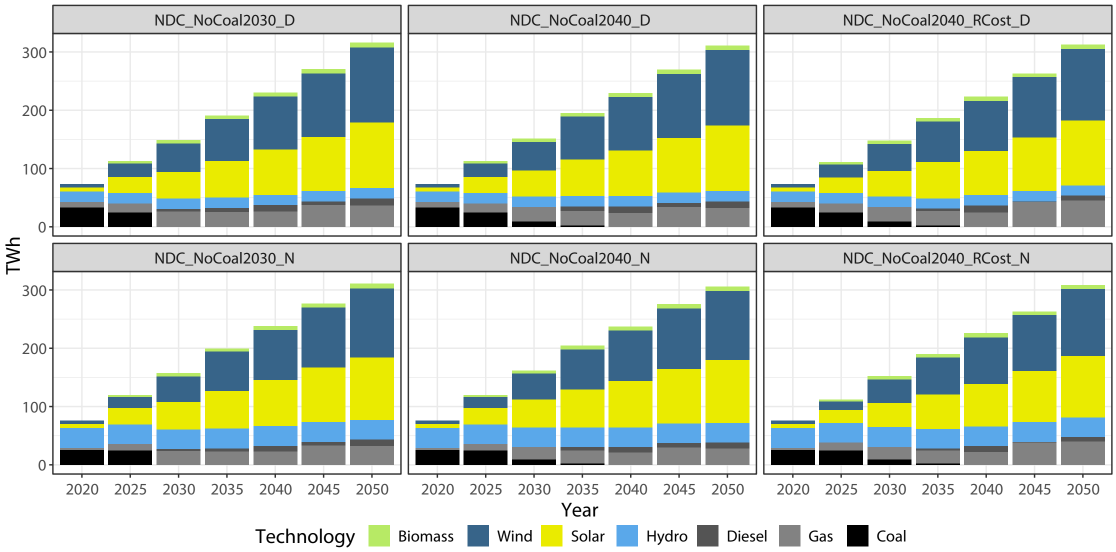


Figure 15: Electricity generation by technology from 2020 to 2050 in NDC scenario by H2RES model

Additionally, Table 5 compares the percentage of solar and wind electricity generation of both GCAM-Chile and H2RES and the total renewable generation in the year 2050 in both cases. The comparison of the shares shows that, in H2RES, there is a slight difference in the percentage of wind power compared to GCAM-Chile in all NDC scenarios of approximately 5%. Similarly, there is a slight decrease in the comparison of solar energy. This difference is, as stated above, mainly because GCAM-Chile considers an annual average capacity factor, which does not represent the hours of highest wind and solar availability, especially in winter in the southern regions of Chile. Another important point is that the total share of renewable energy in H2RES is about 9% lower than in GCAM-Chile. This is also because H2RES requires flexible power plants (gas and diesel) to dispatch electricity to handle the variability from renewable sources. Figure 16 shows the hourly distribution of electricity generation obtained by H2RES for the scenarios of similar hydrology (dry) and different coal phase-out years for the year 2030. From the Figure 16, it can be clearly noted the high variability imposed by the level of solar and wind generation. Also, the fact that solar availability in winter is lower than in summer results in larger levels of gas-based generation occurring in winter periods.

Table 5: Percentage of renewable generation for GCAM and H2RES models

	GCAM (2050)			H2RES (2050)			
Scenarios	**Wind**	**Solar**	**Total renewable**	**Wind**	**Solar**	**Total renewable**	**CEEP**
NDC_NoCoal2030_D	45.80%	39.15%	94.16%	40.69%	35.75%	84.66%	19.64%
NDC_NoCoal2030_N	42.07%	36.62%	94.73%	37.97%	34.66%	85.98%	19.74%
NDC_NoCoal2040_D	45.99%	39.30%	94.53%	41.40%	36.36%	86.05%	20.07%
NDC_NoCoal2040_N	42.27%	36.78%	95.16%	38.58%	35.21%	87.32%	17.31%
NDC_NoCoal2040_RCost_D	45.51%	38.42%	93.61%	39.05%	35.73%	82.86%	22.74%
NDC_NoCoal2040_RCost_N	42.00%	35.68%	94.26%	37.00%	34.28%	84.52%	21.92%

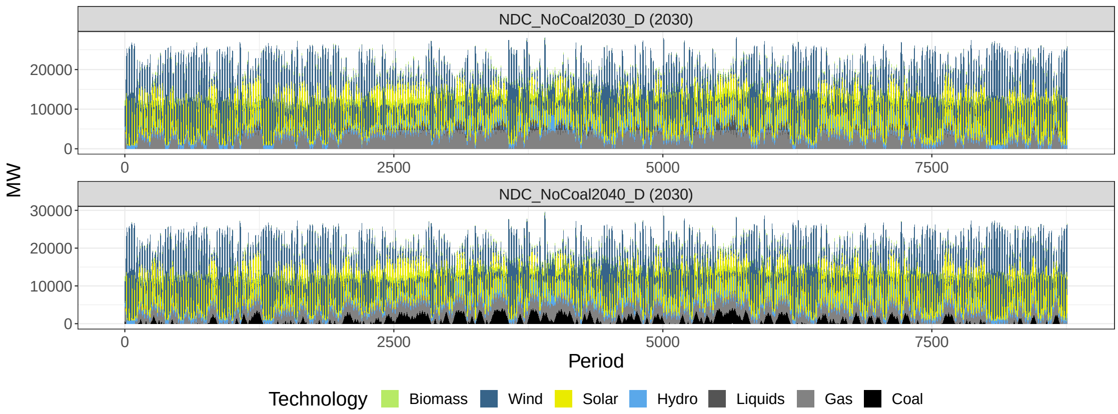


Figure 16: Hourly electricity generation by technology (2030) for dry hydrology

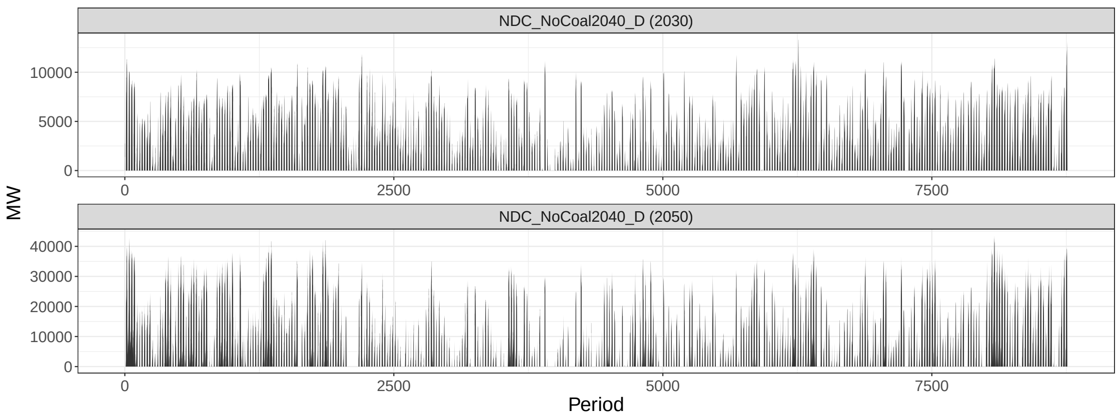


Figure 17: Critical excess electricity production in 2030 and 2050 by periods

For further illustration, Figure 17 shows the hourly level of CEEP for the NDC_NoCoal2040 scenario in the years 2030 and 2050. The higher CEEP at the beginning and end of the year is driven by the peak availability of solar technology (summer and spring seasons). This excess of electricity shows that there are further opportunities to integrate smart and flexible technologies (for instance, smart EV charging) or create room for new markets (such as international exports of H2 or ammonia) to make better use of electricity generation. As expected, the integration of wind and solar energy levels resulted in significant levels of flexibility options. When Power-to-heat, Power-To-H2, fuel cells, and stationary storage are limited, it was not possible to find viable configurations with H2RES that would successfully integrate (balance supply and demand) installed wind and solar capacity. In terms of investment in Power-To-X technologies, it can be noted that all scenarios have different patterns of investments into these technologies over the planning horizon, as shown in Table 6. For example, when comparing the ATW_HP technologies [1] between scenarios NDC_NoCoal2030_D and NDC_NoCoal2040_D, there is a difference of 5% of total capacity by 2050. In the same way, when comparing the electric boilers, there is a difference of 20%. Results also indicate that energy storage plays a significant role in balancing supply and demand in all scenarios. For instance, investment into stationary electricity storage ranges between 11.8 GWh (coal phase put in 2030) to 20 GWh (coal phase-out in 2040) of storage, while 40 GWh of H2 tank storage is required in all scenarios (maximum level of H2 storage allowed to be installed in the scenario design).

Table 6: Investment in Power-To-X technologies for each scenario and each year

Scenario	Technology	2020	2025	2030	2035	2040	2045	2050	Total (MW/MWh*)
NDC_NoCoal2030_D	ATW HP	1592.51	2647.39	1702.07	2519.30	1043.78	566.78	1592.10	11663.93
	electric boilers	163.98	1251.37	0.00	152.67	968.47	290.57	1597.10	4424.16
	geothermal HP	25.92	11.08	33.25	170.71	0.00	0.00	7.18	248.14
	H2 storage*	14.45	170.09	3542.47	36272.99	0.00	0.00	0.00	40000.00
	Alkaline EC	27.09	79.70	270.35	1687.06	1664.75	0.00	258.02	3986.97
	Liion storage*	0.00	0.00	764.23	86.35	5040.37	0.00	5909.81	11800.76
NDC_NoCoal2030_N	ATW HP	559.88	3403.31	1818.37	2747.31	724.55	402.25	2282.07	11937.74
	electric boilers	991.46	1209.42	0.00	0.00	1014.31	479.90	179.25	3874.34
	geothermal HP	25.92	11.14	35.78	173.05	0.00	0.00	0.00	245.89
	H2 storage*	14.20	218.85	3161.64	36605.31	0.00	0.00	0.00	40000.00
	Alkaline EC	26.63	83.42	243.47	1512.34	1742.32	19.42	357.47	3985.07
	Liion storage*	0.00	0.00	988.79	256.28	4926.03	0.00	6027.79	12198.89
NDC_NoCoal2040_D	ATW HP	1592.51	2682.73	1631.44	2606.23	1082.72	316.89	2306.81	12219.33
	electric boilers	163.98	1215.56	0.00	544.77	386.44	609.04	603.66	3523.45
	geothermal HP	25.92	11.08	5.21	199.67	0.00	50.42	18.99	311.29
	H2 storage*	14.45	170.11	2275.65	12267.16	25272.65	0.00	0.00	40000.02
	Alkaline EC	27.09	79.71	184.61	858.48	2690.06	4.69	140.13	3984.77
	Liion storage*	0.00	0.00	0.00	1707.01	7652.95	0.00	10640.04	20000.00
NDC_NoCoal2040_N	ATW HP	559.87	3334.17	1926.54	2792.91	604.20	431.74	2331.89	11981.32
	electric boilers	991.46	1280.71	0.00	0.00	817.11	481.14	0.00	3570.42
	geothermal HP	25.92	11.14	2.86	205.98	0.00	14.11	0.00	260.01
	H2 storage*	14.20	218.80	2230.23	19029.60	18507.17	0.00	0.00	40000.00
	AlkalineEC	26.63	83.40	191.64	1017.64	2520.71	59.43	89.16	3988.61
	Liion storage*	0.00	0.00	0.00	1835.68	6809.48	0.00	11354.84	20000.00
NDC_NoCoal2040_RCost_D	ATW HP	1592.51	2704.11	1432.17	2714.16	617.08	0.00	1138.91	10198.94
	electric boilers	163.98	1106.35	0.00	151.72	1203.23	0.00	714.74	3340.02
	geothermal HP	25.92	11.08	3.20	91.16	0.00	0.00	0.00	131.36
	H2 storage*	14.45	144.53	2232.52	37608.50	0.00	0.00	0.00	40000.00
	AlkalineEC	27.09	78.64	179.85	1803.4	700.79	0.00	0.00	2789.77
	Liion storage*	0.00	0.00	0.00	740.89	3626.31	0.00	0.00	4367.2
NDC_NoCoal2040_RCost_N	ATW HP	559.87	3886.3	1745.23	2513.4	283.67	0.00	959.44	9947.91
	electric boilers	991.46	615.37	0.00	0.00	1376.36	0.00	239.9	3223.09
	geothermal HP	25.92	11.14	2.75	113.46	0.00	0.00	0.00	153.27
	H2 storage*	14.2	172.81	2232.77	36479.59	1100.63	0.00	0.00	40000.00
	AlkalineEC	26.63	82.3	186.71	1750.45	803.39	0.00	0.00	2849.48
	Liion storage*	0.00	0.00	0.00	930.31	3750.79	0.00	0.00	4681.1

[1] ATW HP: Air-to-Water Heat Pump, Geothermal HP: Geothermal Heat Pump, Alkaline EC: Alkaline Electrolysis Cell, Liion storage: lithium-ion Storage.

4.4. Discussion and comparison of results in Chile

In the context of integrated assessment models applied in Chile. To the best of our knowledge, there are four studies. The first study is by Watts and Martinez [97], who used MASSAGE. It differs from our results as it was conducted before the signing of the Paris Agreement and does not consider the current mitigation strategies of Chile. A clear example of this is the generation of electricity, which still includes coal in its energy matrix in 2030, constituting approximately 10% in all scenarios. In contrast, Arriet et al. [23] and Matamala et al. [24] studies consider Chile's mitigation strategies, reflecting the recentness of the 2022 and 2023 studies, respectively. Similar to our study, the authors employ GCAM; however, they use an old version, disaggregating Latin America entirely. In contrast, our study utilizes a new version (GCAM v6.0), disaggregating Chile as a distinct region. Despite this difference, the results are similar in terms of total renewable energy. The difference that exists is in terms of investment in renewable technologies such as mainly solar and the consideration of the use of CCS technology in the studies. The variation in solar outcomes between the two studies arises from the incorporation of Advanced Solar Technology, specifically improved capacity factors, for both Solar Photovoltaic (PV) and Concentrated Solar Power (CSP), estimated at 35% [23]. Similar to our study, the report generated by Kintner-Meyer et al. [25] also used GCAM-Chile to generate decarbonization pathways, nevertheless, the study considers only one hydrology scenario and considers CCS technology. Despite this difference, we can note similarities for each renewable technology, and how fossil fuels are mostly replaced by renewable resources, followed by gas.

On the other hand, in terms of energy system models, there is a large literature dedicated to studying Chile. One of them is by Amigo et al. [44], providing a basis for comparison with our findings. In their research, electricity generation is predominantly composed of approximately 64% solar PV and 28% wind. In contrast, our study using H2RES presents a distinct perspective, revealing an average composition of 35% solar and 40% wind. This variation can be attributed to the costs associated with renewable technologies (medium and low PELP costs), along with the consideration of the progressive phase-out of fossil technologies. Another notable difference is the hourly consideration in H2RES compared to the previous study, enabling the analysis of constraints such as the ramp-up and down of fossil generators. Finally, if we compare with the reports generated by Planificación Energética de Largo Plazo (PELP, long-term energy planning) [80], our results align with the official report of Chile, showing a 5% difference in total electricity generation compared to the carbon-neutral scenario. Similarly, we observe similarities in renewable generation, with a 12% difference in solar and an 8% decrease in wind. Both scenarios project a renewable generation exceeding 80% by 2050.

5. Conclusion

This research highlights the importance of the hourly variability of renewable resources when evaluating carbon neutrality scenarios for 2050. Two models have been used in this research. The first model is an Integrated Assessment Model, a detailed Chilean representation of the Global Change Analysis Model (GCAM). GCAM-Chile allows the simulation of different mitigation strategies. The second is the Highway to Renewable Energy Systems model (H2RES). H2RES is a model for capacity expansion and energy system optimization with an hourly resolution scale of variable renewable sources. The methodology is novel in that it uses a soft-linking approach between GCAM-Chile and H2RES to evaluate how the introduction of hourly resolution affects the outcomes of integrated assessment models. The results show that it is possible to use the capacity obtained from GCAM-Chile and implement it on an hourly scale. However, the feasibility of implementation depends on high levels of flexibility, including stationary batteries, Power-to-heat, and H_2 technologies. Feasible integration of significant renewable sources is obtained with relatively high CEEP levels, reaching 20% in 2050. Additionally, the comparison of the shares reveals that, in H2RES, there is a minor discrepancy in the proportion of wind power compared to GCAM-Chile across all NDC scenarios, approximately 5%. Similarly, there is a slight drop in the comparison of solar energy. This difference is mainly obtained due to GCAM-Chile's utilization of an annual average capacity factor, which fails to accurately capture the hours of peak wind and solar availability. Another notable factor is that the overall contribution of renewable energy in H2RES is roughly 9% lower than in GCAM-Chile. This difference can be attributed to the necessity in H2RES for flexible power plants (such as gas and diesel) to distribute electricity and manage the intermittency associated with renewable sources. The different modeling approaches of renewable sources in GCAM and H2RES result in higher levels of electricity generation in H2RES when compared to GCAM-Chile. Therefore, this indicates that there is room for better integration of the power sector with transport, buildings, and industry sectors by increasing their electrification levels, resulting in a more efficient energy system model with lower levels of CEEP.

This research applied economy-wide constraints, directly impacting emissions produced by the energy and non-energy systems modeled in GCAM-Chile. Nevertheless, our focus was on the energy sector. Therefore, the exploration of the non-energy sector is open for future research. GCAM provides a strong integration of different relevant systems for evaluating mitigation strategies. However, such complexity creates trade-offs. For instance, the main limitation of this research is that GCAM-Chile considers Chile as a single region (not disaggregated into sub-regions). This consideration suggests that the study is focused only on one region, assuming average capacity factors of technologies, rather than planning to focus on the various regions of Chile. This point is vital due to the high potential in the extremes of Chile. For example, solar in the north of Chile and wind in the south of Chile. Similarly, another limitation of the study is its consideration of an ideal scenario without natural disasters, such as earthquakes that are common in Chile and can impact the operation of the electrical system, or wildfires in summer that affect the operation in specific zones. In addition, other sectors, such as the industrial sector, are not considered in this research. Therefore, these aspects will be integrated into future research on H2RES to assess investment and long-term planning. Another limitation of the study is that, when evaluating GCAM results on H2RES, clustered power plants were considered to reduce the computation burden.

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