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Abstract: The objective of the paper is to generate an energy and environmental model using LEAP to forecast energy demand, supply, emissions for Chile by 2030 and create scenarios considering different policies motivated by current policy as well as national and international commitments from Chile. This paper contributes to literature by developing a long-term energy plan including all sectors for Chile, describing energy scenario alternatives and analyzing current policy, nationally determined contributions and sustainable development goals. Results indicate that scenarios with significant energy demand reduction for all sectors showed considerable emission reduction by 2030. In all scenarios, demand sector showed major contribution to emissions when compared to transformation sector. Although emissions from transformation sector demonstrate significant reduction by 2030, decrease in demand side is not clearly noticed for some scenarios. Chile requires appropriate energy efficiency and renewable energy policies for demand sides of sectors especially transport, mining and other industries to reduce emissions at demand-side as having decarbonization for transformation side. Scenarios including more wind, PVsolar, CSPsolar and hydropower plants reached more than 80% renewable electricity generation by 2030. Thus, cleaner production portfolio which results in fewer emissions and more diversification in terms of energy generation can be established in Chile.

26.05.2020

Dear Mr. Henrik Lund
Editors-in-Chief, *Energy*.

We are pleased to submit our revised manuscript entitled "*Comparison of Energy Scenario Alternatives for Chile: towards low-carbon energy transition by 2030*", by Yeliz Simsek, Hasret Sahin, Alvaro Lorca, Wayan G. Santika, Tania Urmee, and Rodrigo Escobar, for publication in **Energy.**

Thanks for all your valuable comments and suggestions to help us improve the quality of our paper. We have considered all your comments and carried out the according to changes in the manuscript. With the help of all suggestions and comments, a new version of the manuscript was prepared carefully. The main changes and improvements are mentioned in detail in the following section.

The revised manuscript reached 7986 words and is slightly over the limit.

We thank the editor and reviewers for helping us advancing and updating this study.

We believe that this paper will be of great interest to a wide range of readers, from academia to policymakers, interested in the energy sector, energy modelling, renewable energy, and energy policy in developing countries. This work can provide meaningful thought for decision-makers and energy-modelling related researchers.

There are no interests to declare for this work.

I testify on behalf of all co-authors that:
• This material has not been published in whole or in part elsewhere,
• After submitting Energy journal, the manuscript is not being considered for publication in another journal,
• All authors have been personally and actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content.

Finally, Y. Simsek acknowledges the financial support of the Chilean National Commission for Scientific and Technological Research under scholarship CONICYT-PCHA/ Doctorado Nacional/ 2018–21181469 to conduct this research, which is also declared in the paper.

Best regards,

Dr Yeliz Simsek
Pontificia Universidad Católica de Chile

Detailed responses to reviewers -Revision 2

Paper "Comparison of Energy Scenario Alternatives for Chile: towards low-carbon energy transition by 2030"

Journal: Energy

By: Yeliz Simsek, Hasret Sahin, Alvaro Lorca, Wayan G. Santika, Tania Urmee, Rodrigo Escobar

Date: 26th of May 2020

Dear Editor and Reviewer,

Thanks for all your valuable comments and suggestions to help us improve the quality of our paper. We have considered all your comments and carried out the according to changes in the manuscript. With the help of all suggestions and comments, a new version of the manuscript (2nd revision) was prepared carefully. The main changes and improvements are mentioned in detail in the following section.

The revised manuscript reached 7986 words and is slightly over the limit.

We thank the editor and reviewer for helping us advancing and updating this study.
In the following parts of this report, comments of reviewer and our detailed answers for the observation can be found.

Best regards,
Dr Yeliz Simsek

Goal and structure of this report

This report includes the comments from the editor and two reviewer of *Energy* regarding the manuscript *"Comparison of Energy Scenario Alternatives for Chile: towards low-carbon energy transition by 2030"* and answers of authors for each comment/suggestion. Thanks for all appreciated comments and suggestions to help us to improve the quality of our paper. We considered all comments and reorganized our work. With the help of all ideas and comments, the new version of the manuscript was formulated carefully. The main changes and improvements are as follows:

Reviewer #2: Reviewer's Comments	**Response to Reviewer 2:**
Reviewer #2: This work generates an energy and environmental model by using LEAP to forecast energy demand. The modifications have been done. Only a particular question, an additional interest of the paper would be to justify the reproducibility of the model in other country contexts. Please analyse this issue in detail as a gap of knowledge and in the discussion section.	The methodology followed in this paper can be applied and reproduced for different countries contexts. In order to create energy and environmental model, initial data such as macroeconomic, demographic and energy balances are required. When such data sets are available for a country, the new model baseline can be developed easily. Also, using LEAP as a modelling tool has an advantage due to having its own "Technology and Environmental Database (TED)" for emission analysis. Also, scenarios can be reproduced by considering the national and international commitments of other countries due to having their own NDC, SDG targets and current policy objectives. Therefore, the reproducibility of the model is emphasized in the introduction, methodology and discussion sections of the paper as follows: In the introduction section: *".... Also, every country which ratified the Paris agreement has its own NDC target and sustainable development goals which reflect in its current energy policy. Therefore, the methodology followed in this research including energy modelling by considering NDC, SDGs and current policy can be applied to those countries and reproduced to create similar scenarios, and from that, the comparison can be developed to inform the policymakers about the progress and gaps."* In the methodology section (3.2. Scenario quantification): *"... To create a model in LEAP, users need to follow the basic structure and initial data sets explained as above. Required initial data (demographic, macroeconomic and energy balance data) can be obtained from national governmental and international institutions. This basic structure makes the model easier for reproducibility and replicability, and it enables the adoption of*

	the LEAP model in various countries. " In the discussion section: *"…Finally, the methodology followed in this paper can be adopted and reproduced for different countries contexts. When initial data sets including macroeconomic, demographic and energy balances are available for a country, the new model baseline can be replicated easily. Also, scenarios can be reproduced by considering the national and international commitments of other countries due to having their own NDC, SDG targets and current policy objectives."*

Highlights

- Scenarios with energy demand reduction showed considerable emission reduction by 2030
- In all scenarios, demand sector showed major contribution to emissions
- Emissions from transformation sector demonstrate significant reduction by 2030
- Chile requires appropriate energy efficiency, renewable energy policies for demand side
- 80% renewable electricity generation is reached including more renewables by 2030

Comparison of Energy Scenario Alternatives for Chile: towards low-carbon energy transition by 2030

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Abstract

The objective of the paper is to generate an energy and environmental model using LEAP to forecast energy demand, supply, emissions for Chile by 2030 and create scenarios considering different policies motivated by current policy as well as national and international commitments from Chile. This paper contributes to literature by developing a long-term energy plan including all sectors for Chile, describing energy scenario alternatives and ~~analyzing~~ analyzing current policy, nationally determined contributions and sustainable development goals. Results indicate that scenarios with significant energy demand reduction for all sectors showed considerable emission reduction by 2030. In all scenarios, demand sector showed major contribution to emissions when compared to transformation sector. Although emissions from transformation sector demonstrate significant reduction by 2030, decrease in demand side is not clearly noticed for some scenarios. Chile requires appropriate energy efficiency and renewable energy policies for demand sides of sectors especially transport, mining and other industries to reduce emissions at demand-side as having ~~decarbonization~~ decarbonization for transformation side. Scenarios including more wind, PVsolar, CSPsolar and hydropower plants reached more than 80% renewable electricity generation by 2030. Thus, cleaner production portfolio which results in fewer emissions and more diversification in terms of energy generation can be established in Chile.

Keywords: *Energy modelling, Scenario alternatives, Decarbonization, LEAP, NDCs, SDGs*

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1. Introduction

Climate change is one of the worldwide challenges for humanity in recent years. Human activities in the energy sector are vital to contributing greenhouse gas (GHG) emissions, which are mostly produced by fossil fuel combustion in, particularly, industry, transportation and electricity generation sectors [1]. Approximately 81% of global energy demand is met by fossil fuels including oil, coal, and gas [2]. Growing demand, tentative fuel price, and the rising concern about climate change are pushing countries to have long-term and sustainable energy planning. Therefore, many ~~industrialized~~ industrialized and developing countries have started to change their future energy plans towards de~~-~~carboni~~z~~zation by ~~analysing~~ analyzing several alternatives scenarios to see the impact of national and international commitments on energy plans [3]. In parallel to the developments in the world, Chile also began to take actions. After the Chilean Ministry of Energy was created in 2010, activities related to long-term energy planning have accelerated [4,5].

In the latest years, significant improvements in energy policy development can be observed in Chile [3]. MAPS-Chile can be considered as the first project that developed projections and mitigation action plans to reduce greenhouse gas emissions in Chile [6–8]. In 2014, the Energy Ministry of Chile decided to develop an agenda to define a new role for the Chilean government and the goals for future energy policy [9]. Energy Agenda 2050 was followed by The Road Map (Hoja de Ruta) and Energy 2050 studies which contained the key items of the long-term energy policy as promised in Energy Agenda [10]. In 2017, Chile ratified the Paris Agreement and committed to develop policies on climate change and to achieve sustainable development objectives. With this agreement, Chile proposed a target that represents a reduction of 30% in greenhouse gas (GHG) emissions below 2007 levels by 2030, and also to apply carbon taxes of USD 5/tCO_2 for fixed turbines or boilers above 50 MWth [11]. Besides international promises, Chile also set a national target to develop a long-term energy planning every five years for different energy scenarios that include expansion of generation and energy demand, in a horizon of at least thirty years [12]. After the elections in 2017, the new government announced Energy Route 2018-2022, in which the main axes of the new energy route were defined as follows: energy ~~modernization~~modernization, energy with a social seal, energy development, efficient transportation, low energy emissions, energy efficiency, and energy education and training [13]. Moreover, promoting renewable energy and energy efficiency were addressed as essential strategies for Chile to reduce emissions and reach its energy and environmental goals in various governmental studies [3].

Chile has divided into fifteen regions from north to south, and it has three main electricity grids: National Electricity System (SEN), the Aysen System (SEA), and the Magallanes System (SEM). Among these three grids, the National Electricity System includes thirteen regions and controls 99% of the total electricity supply of Chile [14]. The primary energy supply of Chile mainly consists of oil, coal, natural gas, biomass, hydro, and it has diversified in recent years with the inclusion of renewable energy such as solar, and wind sources. These sources are consumed in five main sectors in Chile: industry, mining, commercial and public, residential, and transport. Industry and transport represent the biggest shares in the total consumption of energy, and mining, which take place mostly in the northern regions of Chile [15,16], and presents heavily energy-intensive activities. Chile mainly depends on imported fuels for energy supply with an approximate proportion of 71% in 2017. Oil is the main energy source in the energy balance, and it is followed by biomass (mainly firewood), coal, natural gas, and hydro, respectively.

Chile has considerable renewable energy potential [3]. Especially, the north of Chile has the best worldwide solar energy potential for energy generation, on account of dryness and clear sky [17,18]. According to a joint study by the Ministry of Energy and the German Agency for International Co-operation in 2014, solar photovoltaic (PV) potential was estimated at 1263 GW, concentrated solar power at 548 GW, wind power at 37 GW (capacity factor of at least 30%), and small hydropower at 12 GW [19,20]. Additionally, it was projected that Chile has a potential of 164 GW from the ocean due to its long Pacific coast, 16 GW from geothermal sources due to containing 10% of the most active volcanoes in the world, and 1.4 GW from biomass sources [21].

After the national and international commitments of several countries in the latest years, studies in the field of energy modelling and planning increased in the literature. There are some recently published studies related to power generation and electricity expansion planning for Chile [22–29]. However, there is no published research about long-term energy planning, demand and supply forecasting or energy scenario alternatives for Chile including all energy sectors. Additionally, studies which ~~analyse~~ analyze and compare national/international commitments such as nationally determined contributions (NDCs), current energy policies and sustainable development goals (SDGs) do not exist in the literature for Chile so far. ~~Finally, a~~Although some energy models including current policy and NDCs of countries exist in the literature, implementing sustainable development goals to the energy model is a significant novelty in terms of contribution to the literature.

Also, every country which ratified the Paris agreement has its own NDC target and sustainable development goals which reflect in its current energy policy. Therefore, the methodology followed in this research including energy modelling by considering NDC, SDGs and current policy can be applied to those countries and reproduced to create similar scenarios, and from that, the comparison can be developed to inform the policymakers about the progress and gaps.

Motivated by this gap in the literature, this research contributes to the state-of-the-art by generating ~~an~~ energy and environmental model for Chile and ~~analysing~~ analyzing different scenario alternatives which include energy strategies such as current policies, nationally determined contributions, sustainable development goals, and ~~decarbonization~~decarbonization. The contributions of this study to the literature can be listed as follows: 1)

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creating an energy model for all Chilean energy sector to forecast energy demand and supply by 2030 by using LEAP, 2) to ~~analyse~~ analyze different policies, energy-saving potential and ~~decarbonization~~ decarbonization impact on energy planning for alternative scenarios in Chile such as current policy, NDCs and SDGs, and 3) to evaluate and compare the determined scenarios if they meet their energy and environmental targets.

The reminder of the paper is ~~organized~~ organized as follows: Section 1 is an introduction to the paper which provides a background of the energy sector in Chile, relevance and objectives of the research, and contribution to the literature. Section 2 provides the methodology applied including a revision of long-term energy planning models and studies in the literature, modelling and scenarios for Chile. Section 3 presents and discusses in detail the results of the energy model work. Finally, section 4 is the conclusion of the analysis, and it proposes further research subjects.

2. Literature review

In order to choose a suitable modelling tool, energy system models and studies in the literature were reviewed. In the literature, although there are several ~~categorizations~~ categorizations for energy planning modelling, long-term energy planning approaches and models can be distributed into seven main categories, including simulation (e.g., RAMSES, BALMOREL, LEAP, WASP, etc.), scenario (e.g., MARKAL/TIMES, MESSAGE, LEAP, etc.), equilibrium (e.g., MARKAL, PRIMES, etc.), top-down (ENPEP-BALANCE, LEAP, etc.), bottom-up (HOMER, RAMSES, MARKAL/TIMES, MESSAGE, etc.), operation ~~optimisation~~ optimization (BALMOREL, MESSAGE, RAMSES, etc.), and investment ~~optimisation~~ optimization tools (MESSAGE, MARKAL/TIMES, RETScreen, etc.) as ~~categorized~~ categorized in References [30,31].

In Table 1, some energy modelling studies obtained from literature in the last years were listed. Depending on the research objective, modelling can be done for all energy, just electricity, only demand or just one energy sector such as industry. As presented in the table, both developed (UK, Ireland, Taiwan) [32–34] and developing countries (Greece, Iran, Turkey, Ethiopia, Bangladesh, Pakistan, Indonesia, Colombia etc.) [30,35–40] were studied as a case study. In the last years, besides several LEAP studies, models which ~~utilized~~ utilized TIMES, MARKAL, MESSAGE and some developed ~~optimization~~ optimization models also exist in the literature. For instance, Amirnekooei et al. worked on several demand and supply-side management strategies including the ~~utilization~~ utilization of electric stoves in place of natural gas-fuelled stoves, employment of coal power plants the ~~utilization~~ utilization of hydro-pump storage and integrating gas turbine plants to combined-cycle ones for Iran by using LEAP. The results showed the natural gas and crude oil savings while considering these strategies in Iran [35]. Roinioti et al. studied Greece all energy system and developed scenarios by considering the different target of emission reduction and economic growth. The study presented that scenarios with high renewable energy penetration decrease CO_2 emissions while the capital cost is increasing [41]. Tsai and Chang investigated emission mitigation measures of Taiwan by 2030. The study included both technologies and tax measures. All sectors in

Taiwan require to decrease energy intensities below the BAU scenario by 48% to 53% to meet its carbon reduction targets for 2050 [33]. Nieves et al. worked on demand and emission forecasting by considering the main energy sectors (industry, housing, and transport). Each sector studied separately based on scenarios including low-high economic growth and potential incentives for new technologies [39].

On the other hand, although any scientific study related to all energy sector modelling for Chile does not exist in the literature so far, there are some recently published studies related to power generation and electricity expansion planning for Chile [22–29]. Most of these studies are developed based on optimization optimization models. For instance, Quiroga et al. worked on projections of the Chilean electric system's expansion without and with taxes, and demand growth estimation. The results showed that the availability of renewable energy capacity could improve the effectiveness of pollutant taxes. Verastegui et al. studied the Chilean power system expansion by 2040 by considering the government´s decarbonization decarbonization plan. The research showed interesting results of the generation portfolio based on phasing out coal power plants by 2030, 2035 or 2040 [29]. O´Ryan et al. investigated renewable energy penetration on power expansion planning in Chile. CO_2 emissions of developed scenarios are obtained 10-15% less than business as usual scenario due to the significant share of renewables in the energy portfolio of developed scenarios [28].

In this study, LEAP was chosen as a modelling tool. LEAP is a software, developed by the Stockholm Environment Institute, Boston, to analyse analyze energy demand and supply, energy policy, resource extraction, and accounting GHGs emissions [42]. LEAP has following advantages: permitting scenario analysis in terms of energy, environment and economy, having ability to follow energy consumption, production and resource extraction in all sectors, requiring less initial data input, providing a Technology and Environmental Database (TED) which offers up-to-date energy technologies data from a wide range of sources, affording data visualization visualization for end-users [31], and finally being free of charge for academics and PhD students.

Table 1. Some energy modelling studies in the literature

Scenario approach	**Sector**	**Country**	***Model***	***Reference***
Renewable energy penetration in Crete's electric system	Electricity	Greece	*LEAP*	[43]
Resource planning integration	Energy	Iran	*LEAP*	[35]
Scenarios including uncertain aspects and technology options for clean energy usage	Energy	Greece	*LEAP*	[41]
Climate mitigation and global warming minimization minimization potential	Electricity	Panama	*LEAP*	[44]

Sustainable energy scenario options to meet the challenges of both energy security and means of climate change mitigation	Energy	Ethiopia	*LEAP*	[36]
Energy efficiency and CO_2 mitigation potential in the industry sector	Energy in Industry sector	Turkey	*LEAP*	[45]
The impact of renewable energy, energy conservation and efficient technologies	Electricity	Bangladesh	*LEAP*	[37]
Renewables for energy security and carbon mitigation	Electricity	Indonesia and Thailand	*LEAP*	[46]
Moderate energy access, accelerate energy access policies, renewable energies promotion and energy efficiency policies	Energy (Demand)	Africa	*LEAP*	[30]
Renewable Energy Potential for Thailand's NDC	Energy (Demand)	Thailand	*LEAP*	[47]
Policy analysis including renewable energy clean coal, energy efficiency and conservation	Electricity	Pakistan	*LEAP*	[38]
Reduction targets for greenhouse gas emissions for 2020 and 2050	Energy	Ireland	*TIMES*	[48]
Climate and energy scenarios for 2050	Energy	Ireland	*TIMES*	[32]
Scenarios with different policies: CO_2 emission reduction constraint, renewable energy production targets etc.	Electricity	United Arab Emirates	*MARKAL*	[49]
Low carbon development roadmap	Energy	Taiwan	*MARKAL*	[33]
Emission reduction scenarios	Energy	UK	*MARKAL*	[34]
Energy technology options under different scenarios	Electricity	India	*MESSAGE*	[50]
Energy mix and nuclear option in Malaysia taking into account the national energy policies	Energy (Demand)	Malaysia	*MESSAGE*	[51]
Energy supply strategies by considering ~~minimized~~ minimized the total system costs	Energy (Supply)	Syria	*MESSAGE*	[52]
New energy strategies introduced by the government including the nuclear power plant, hydropower and renewable energy	Electricity	Malaysia	*MESSAGE*	[53]
Scenarios with the lowest cost of generation and	Electricity	Indonesia	~~*Optimization*~~ *Optimization*	[40]

the lowest CO_2 emissions			*Model*	
Power system expansion planning under global and local emission mitigation policies	Electricity	Chile	~~*Optimization*~~ *Optimization model*	[24]
~~Analysing~~ Analyzing the energy demand and greenhouse gas emissions	Energy	Colombia	*LEAP*	[39]

3. Methodology

The methodological approach in this research is mainly based on a literature review, scenario description, scenario quantification, verification of model reliability, results and comparison, as illustrated in Figure 1. The literature review is explained in the previous section in order to give more information about energy modelling researches in the literature and energy/electricity studies about Chile. The following steps of the methodology are explained in additional detail within the following sections.

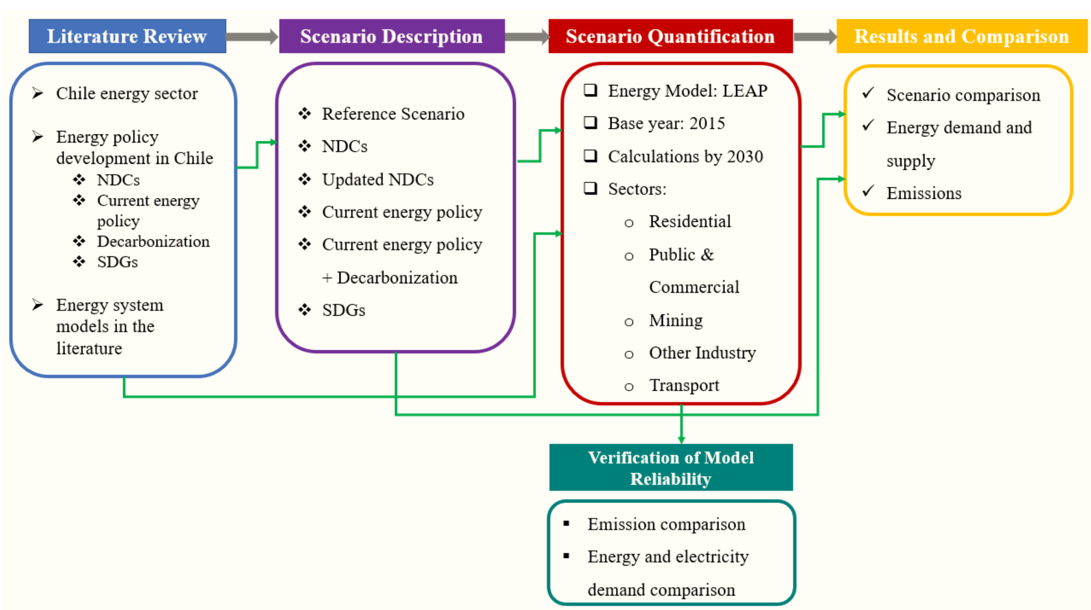

Figure 1. Flowchart of the methodological approach

3.1. Scenario description

The main step of the methodology is the scenario description in which each scenario was determined based on reviewed information. At this stage, current policy, current NDC, updated NDC, and ~~decarbonization~~ decarbonization plans of Chile were reviewed from published international and government reports and these strategies were added to the scenarios. Additionally, the energy requirement to meet energy-related Sustainable Development Goals was investigated to make a further scenario in the model to compare to other scenarios. Finally, six different scenarios were determined as follows and the comparison of scenarios can be seen in Table 2:

Reference Scenario (Ref): This scenario takes into account the shift in the energy sector between 2008 and 2015 and calculates the energy sector estimates for 2030 according to this trend. It also ignores current policy, new policy, international and national promises by 2030.

Nationally Determined Contributions (NDCs) Scenario: This scenario considers some actions and targets of NDCs of Chile, which was presented to the United Nations Framework Convention on Climate Change in 2015 [3,11].This scenario considers 30% emission reduction by 2030, reduction of projected energy consumption, electricity demand growth for the transportation sector, renewable energy promotion, energy efficiency and no ~~decarbonization~~ decarbonization as presented in Table 2.

New NDCs Scenario: In October 2019, Chile proposed an updated NDCs based on the previous promises. This scenario takes into account renewed NDCs which includes a 45% reduction in GHG when it is compared to 2016 [54]. In order to have considerable emission reduction, besides NDC, efficient usage of energy, biomass usage restriction in the residential sector, and significant energy demand reduction were considered in this scenario.

Current Policy Scenario: This scenario considers the last energy plan of the former government (Energy 2050) and the first energy plan of the new government of Chile (Route 2018-2022) [55,56]. Based on these plans, 30% emission reduction, 30% energy demand reduction in the residential sector, energy efficiency in major sectors, fossil fuels replacement with electricity, 57% electricity generation from renewable energy by 2030, fast improvement on transmission and distribution (T&D) lines, and restriction on biomass usage in the residential sector were considered.

Current Policy + Decarbonization Scenario: The government decided to start the process of ~~decarbonization~~ decarbonization of the energy matrix through the preparation of a timetable for the withdrawal or reconversion of coal-fired plants. According to the ~~decarbonization~~ decarbonization plan, all coal power plants will be phased out by 2040. Therefore, in this scenario, besides all requirements of the current policy, the new ~~decarbonization~~ decarbonization plan of government which takes into account phasing out 1047 MW coal power plants by 2024 is also considered [55–57] and also additional coal phase-out in which coal power plant capacity is reduced to 2500 MW by 2030 is considered.

SDGs Scenario: Based on our previous study, Chile requires approximately 16,048,414.24 Gigajoules additional energy to meet energy-related SDGs, which increase energy demand by 2030. This scenario takes into account all current policies, decarbonization decarbonization and also additional demand to meet energy-related Sustainable Development Goals (SDGs) by 2030. This extra energy demand impacts other industry, residential and commercial sectors as explained in Appendix A (TableA1).

Table 2. The summary of scenario description

	Reference Scenario	NDCs Scenario [58]	New NDCs Scenario [54]	Current Policy Scenario [55,56]	Current Policy + Decarbonization Scenario [55–57]	SDGs Scenario
Emission reduction *"It is a control mechanism to check if the scenario is meeting emission reduction."*	No emission reduction is considered.	30% emission reduction by 2030 compared to 2007. (with international support 35-45% reduction).	45% emission reduction by 2030 compared to 2016.	30% emission reduction by 2030 compared to 2007. (with international support 35-45% reduction).	30% emission reduction by 2030 compared to 2007. (with international support 35-45% reduction).	30% emission reduction by 2030 compared to 2007. (with international support 35-45% reduction).
Change in demand *"It refers to the demand changing in the scenario based on determined targets due to the energy efficiency of electricity or energy demand. "*	Not considered	20% reduction of projected energy consumption (total demand) by 2025. This reduction is realized by considering the reduction in the following sectors and fuels: - Residential: electricity and biomass share - P&C: electricity share - Mining: electricity and diesel share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share	Total 38.5% reduction of projected energy consumption (total demand) by 2030. This scenario includes energy demand decrease of NDC scenario and additional energy demand reductions from each sector to meet emission target as follows: Residential: 15% P&C: 15% Mining: 15% Other Industry: 15% Transport: 20%	Energy demand change in this scenario comes from 30% reduction from residential demand by 2022 and other sectors energy efficiency. Also, efficient usage of energy in major sectors are considered as NDC scenario. This reduction is realized by considering the reduction in the following sectors and fuels: - Residential: kerosene, LPG, electricity, natural gas, biomass share - P&C: electricity share - Mining: electricity and diesel share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share	Energy demand change in this scenario comes from a 30% reduction from residential demand by 2022 and other sectors energy efficiency. Also, efficient usage of energy in major sectors are considered as NDC scenario. This reduction is realized by considering the reduction in the following sectors and fuels: - Residential: kerosene, LPG, electricity, natural gas, biomass share - P&C: electricity share - Mining: electricity and diesel share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share	Energy demand change in this scenario comes from - The additional energy requirement to meet energy-related SDGs. - 30% reduction from residential demand by 2022. - Also, efficient usage of energy in major sectors are considered. This reduction is realized by considering the reduction in the following sectors and fuels: - Residential: kerosene, LPG, electricity, natural gas, biomass share - P&C: electricity share - Mining: electricity share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share

Transportation *"It considers any change in the transport sector due to electricity demand for EV or fossil fuel phase-out targets."*	Not considered	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) is decreased due to the increase of electricity share.	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) is decreased due to the increase of electricity share.	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) is decreased due to the increase in electricity share.	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) was decreased due to the increase in electricity share.	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) is decreased due to the increase in electricity share.
Capacity and Generation Mix *"It shows the change in the current electricity share portfolio by decreasing or increasing the current installed capacity."*	Real installed capacity and generation values were entered to the LEAP until 2018. Also, the capacity between 2018 and 2030 is increased based on the compound annual growth rate (CAGR).	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Finally, the capacity remained the same between 2024-2030. 20% of the energy matrix in the generation is made up of unconventional renewable energies by 2025.	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Finally, the capacity remained the same between 2024-2030. 20% of the energy matrix in the generation is made up of unconventional renewable energies by 2025.	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Moreover, additional capacities are added for solar PV, solar CSP, wind and hydro between 2024-2030. 57% of electricity generation from renewable energy by 2030. At least 50% of the fuels in the energy matrix should be low in GHG emissions and atmospheric pollutants.	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Moreover, additional capacities are added for solar PV, solar CSP, wind and hydro between 2024-2030. 57% of electricity generation from renewable energy by 2030. At least 50% of the fuels in the energy matrix should be low in GHG emissions and atmospheric pollutants. Decarbonization is realized based on governments plan by 2024 and an additional plan is considered by 2030 [29,57].	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Moreover, additional capacities are added for solar PV, solar CSP, wind and hydro between 2024-2030. 57% of electricity generation from renewable energy by 2030. At least 50% of the fuels in the energy matrix should be low in GHG emissions and atmospheric pollutants. Decarbonization is realized based on governments plan by 2024 and an additional plan is considered by 2030 [29,57].
Transmission and Distribution (T&D) Losses	Improvement in T&D losses are not considered	T&D losses are considered 4.5% by 2030 (Moderate improvement on T&D lines)	T&D losses are considered 4.5% by 2030 (Moderate improvement on T&D lines)	Historical growth is considered, and the losses reached 3.8% by 2030 (Fast improvement on T&D lines)	Historical growth is considered, and the losses reached 3.8% by 2030 (Fast improvement on T&D lines)	Historical growth is considered, and the losses reached 3.8% by 2030 (Fast improvement on T&D lines)

Fossil fuel transformation *"It addresses changing the total share of fossil fuel power plants in the current net generation. It can be executed by decommissioning the fossil fuel power plants installed capacity or using more clean fuels."*	No fossil fuel transformation is considered	Additional coal phase-out is not considered in this scenario.	Additional coal phase-out is not considered in this scenario.	Additional coal phase-out is not considered in this scenario.	1047 MW coal power plant capacity is phased out until 2024 (planned by the government) and also additional coal phase out is considered by 2030. Thus, total coal capacity is reduced to 2500 MW by 2030. Natural gas/diesel remained at the same capacity.	1047 MW coal power plant capacity is phased out until 2024 (planned by the government) and also additional coal phase out is considered by 2030. Thus, total coal capacity is reduced to 2500 MW by 2030. Natural gas/diesel remained at the same capacity.
Energy Efficiency (EE)	EE is not considered	EE is considered for all sectors. Biomass usage was restricted in the residential sector.	2020 EE action plan target is considered [60]. Biomass usage was restricted in the residential sector.	2020 EE action plan target is considered [60]. Biomass usage was restricted in the residential and other industry sector.	2020 EE action plan target is considered [60]. Biomass usage was restricted in the residential and other industry sector	2020 EE action plan target is considered [60]. Biomass usage was restricted in the residential and other industry sector

3.2. Scenario quantification

Scenario quantification was performed as the third step of the methodology by generating an energy model by using LEAP for the Chilean energy sector. The developed LEAP model for Chile includes historical energy sector data from 2008 and 2015, considers 2015 as the base year, and ~~realize~~ realize forecasting for 2030. The model includes five main energy sectors in Chile: residential, public and commercial (P&C), mining, industry and transportation. Also, non-energy usage and auto consumption sectors were added due to having in the national energy balances. Chile has almost 29% of the world's copper reserves, and it is the largest copper producer and exporter, having produced 37% of the world's copper in 2016 [19,61]. Thus, the mining sector was ~~analysed~~ analyzed in the model separately from other industry sectors. The defined scenarios from the previous step were quantified and implemented to the developed energy model.

Figure 2 shows the structure of the LEAP model. LEAP requires demographic (population) and macroeconomic (GDP, sectoral GDP) data for the baseline of the model [42]. These data are used as inputs for demand analysis. Also, activity levels and energy intensity of each sector are required for demand analysis. In this study, activity level and energy intensities are assumed as listed in Table 3. The population was assumed as activity level for residential, public and commercial sectors when sectoral GDP shares were accepted as activity level for mining, industry and transportation sectors. Also, auto consumption and non-energy sectors mentioned in the energy balance were quantified with their total energy values in the model.

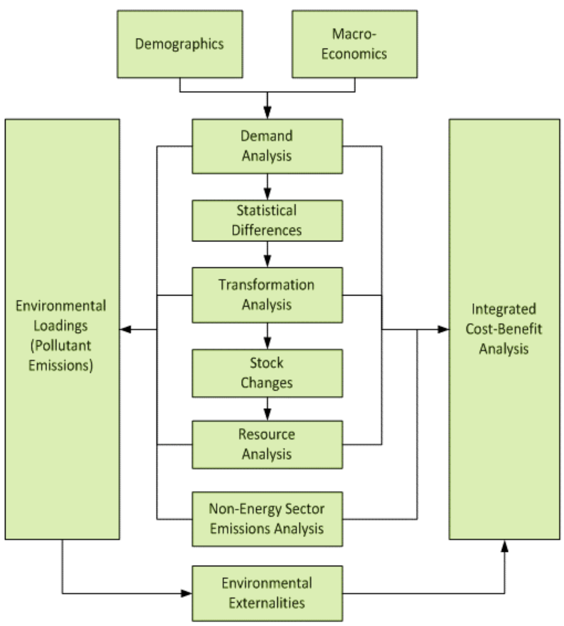

Figure 2. The structure of LEAP calculations [42]

Table 3. Activity level and energy intensity assumptions in the LEAP model

	Activity Level	Energy Intensity
Residential	Population (person)	$Energy_{total}$/Population (GJ/person)
Public and Commercial	Population (person)	$Energy_{total}$/Population (GJ/person)
Mining	GDP*Sectoral GDP share (US$)	$Energy_{total}$/Sectoral GDP (GJ/US$)
Industry	GDP*Sectoral GDP share (US$)	$Energy_{total}$/Sectoral GDP (GJ/US$)
Transport	GDP*Sectoral GDP share (US$)	$Energy_{total}$/Sectoral GDP (GJ/US$)
Auto consumption	Total Energy (Tcal, GJ)	
Non-energy	Total Energy (Tcal, GJ)	

Besides key assumptions such as demographics and macroeconomic data, LEAP requires historical energy demand and transformation data to forecast future values. Transformation analysis follows demand analysis as shown in Figure 2. It includes electricity generation, transmission and distribution losses of the system. For transformation analysis, technical parameters such as lifetime, efficiency, availability and cost values of power plants are required. The model is also suitable for emission analysis. LEAP allows generating several scenarios with the created model and compares the results based on energy and environmental outputs.

The equations considered in the LEAP model for energy demand, net energy consumption for transformation, carbon emissions from final energy consumption, and carbon emission from energy transformation are presented as follows [30,31,42]**.**

Energy demand is a function of activity level and energy intensity for each sector, and it is calculated as Eq (1):

$$\mathrm{ED}_{b,s,t} = \mathrm{TA}_{b,s,t} * \mathrm{EI}_{b,s,t} \tag{1}$$

ED: energy demand (GJ)

TA: total activity (person or US$)

EI: energy intensity (GJ/person or GJ/US$)

Also, b is the branch, s is the scenario, and t is the year.

Additionally, the net energy consumption for transformation is calculated as Eq (2):

$$\mathrm{ET_p} = ETP_{sec,tec} * \left[\frac{1}{f_{p,\mathrm{sec,tec}}} - 1\right] \tag{2}$$

ET: net consumption for transformation (energy loss for a transformation process) (GWh)

ETP: product from the transformation process (GWh)

Also, f is energy transformation efficiency, tec is the technology, p is the type of primary energy, and sec is the type of secondary energy.

Moreover, the carbon emissions from final energy consumption are calculated from Eq (3):

$$\mathrm{CE}_{p,s,t} = \mathrm{TA}_{b,s,t} * \mathrm{EI}_{b,s,t} * \mathrm{EF}_{b,s,t} \quad (3)$$

CE: carbon emissions (MMetric Tonnes CO_2 eq)

$EF_{b,s,t}$: carbon emissions factor from the sector or branch b, scenario s and year t.

Finally, the emissions from energy transformation are calculated in LEAP as shown in equation 4:

$$\mathrm{CET} = ETP_{sec,tec} * \frac{1}{f_{p,\mathrm{sec},\mathrm{tec}}} * EF_{p,sec,tec} \quad (4)$$

CET: the carbon emission (MMetric Tonnes CO_2 eq)

$EF_{p,\,sec,\,tec}$: the emission factor from one unit of primary fuel type p, used to produce the secondary fuel type sec through the technology tec.

Relevant quantitative and qualitative information for modelling were gathered via scientific databases (Science Direct and Research Gate), open-access search engines (Google and Google Scholar), open access international ~~organisation~~ organization reports, and publicly available Chilean governments´ reports. For instance, national energy balances are reported annually on the website of the National Energy Commission of Chile [62]. Demographic data are obtained from the National Statistics Institutes of Chile and the World Bank Group [63,64]. Macroeconomic data are taken from international statistic websites, Chilean government report and ministries publicly available documents [65–67]. Moreover, the required data for the transformation part of the model, such as power plant installed capacities and historical generation, are acquired from the reports and website of the National Energy Commission of Chile [68]. Technology and power plant information such as availability, efficiency are taken from published peer-reviewed articles, LEAP database, and international thesis [42,69,70]. Finally, emission impact data is taken from the available database in the LEAP model: Technology and Environmental Database [42].

To create a model in LEAP, users need to follow the basic structure and initial data sets explained as above. Required initial data (demographic, macroeconomic and energy balance data) can be obtained from national governmental and international institutions. This basic structure makes the model easier for reproducibility and replicability, and it enables the adoption of the LEAP model in various countries.

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After quantifying all defined scenarios, the results including energy demand and supply, emissions for each scenario were compared, and the detailed results were given in the following section.

4. Results and Discussion

By using the collected and collated information, six scenarios with different strategies for a 15-year horizon have been obtained from the generated energy model. The main results are presented and compared in this section.

4.1. Reliability check for the energy model

Before presenting the results, the approach to check the accuracy of the model is also explained in this section. In order to verify the reliability of the created energy model, energy/electricity demand projections for 2030, and CO_2 emission values for base case are compared to published government reports and United Nations Framework Convention on Climate Change (UNFCCC) country emission reports.

Table 4 presents CO_2 emission (without LULUCF / LUCF) values obtained from UNFCCC and LEAP results for base years. In LEAP Chile model, 2015 is assumed as the base year of the model. And the first calculations are ~~realized~~ realized for the year 2016. In order to check the reliability of the model, emission values between 2010 and 2015 are calculated based on Technology and Environmental Database (TED) of LEAP and the difference between the real (UNFCCC values) [71] and calculated values (LEAP result) are presented in the table. LEAP results showed higher emission values with 3-5.5% error margin between 2010 and 2013. On the contrary, LEAP values are obtained lower than UNFCCC values with a 1.5-2.2% error margin for 2014 and 2015.

Table 4. CO_2 emissions (without LULUCF / LUCF) values obtained from UNFCCC and LEAP results for base case (MMetric Tonnes CO_2)

Year	UNFCCC values [71]	LEAP results	% error
2010	69.67	71.94	3.26%
2011	73.50	77.58	5.55%
2012	77.00	79.30	2.99%
2013	80.50	84.42	4.87%
2014	83.00	81.75	-1.51%
2015	85.30	83.43	-2.19%

Additionally, energy and electricity demand values are compared for LEAP reference scenario results and government´s national energy balances, as presented in Table 5. As mentioned above, 2015 is assumed as the base year and the model calculates the demand results for 2016 and beyond, that allows comparing real and calculated values. Reference scenario energy demand is obtained higher values than the values in 2016-2017 Chilean National Energy balances [15,72] with 0.23% and 0.27% error margin, accordingly.

Table 5. Energy and electricity demand comparison for real and calculated values

Year	Energy Demand (Tcal)	LEAP energy demand results (Tcal)	Error (%)	Electricity Demand (GWh)	LEAP Electricity Demand (GWh)	Error (%)
2016	284,778 [15]	285,430	0.23%	-	-	-
2017	288,901 [72]	289,670	0.27%	-	-	-

2030	*350,000 (low)*- 400,000 (high) [12]	344,760	-1.50%	*100,000 (low)*- 115,000 (high) [12]	95,388	-4.61%

Also, the calculated energy demand (LEAP reference scenario result) for 2030 is compared to government energy projection. Depending on the low, medium and high demand projection, the report indicated that energy demand for 2030 would vary between 350,000-400,000 Tcal [12]. When the low energy demand projection of government for 2030 is compared to LEAP result, -1.50% error margin is obtained for the calculated value. Finally, the projected and calculated electricity demand for 2030 are compared. The electricity demand for 2030 is obtained 95,388 GWh from LEAP when it was envisaged as 100,000-115,000 GWh depending on low, medium and high electricity demand scenarios [12]. When low electricity demand projection of government is compared to the calculated value, LEAP results showed lower demand value for electricity with a -4.61% error margin for 2030.

4.2. Comparison of scenarios

Figure 3 shows the total energy demand projection for all scenarios between 2010 and 2030. Without considering any policy for efficient use of energy, total energy demand will reach approximately 1450 million GJ as shown in the reference scenario. Other scenarios showed significant decreases due to having reduction targets on energy demand. NDC scenario is obtained as the second highest energy demand by 2030 although it has a 20% energy saving target by 2025. Due to its major emission reduction target, the new NDC scenario should have at least a 38.5% reduction in energy demand when it is compared to the reference scenario by 2030. Thus, the new NDC policy shows the lowest demand for 2030 which is 887 million GJ when it is compared to other scenarios.

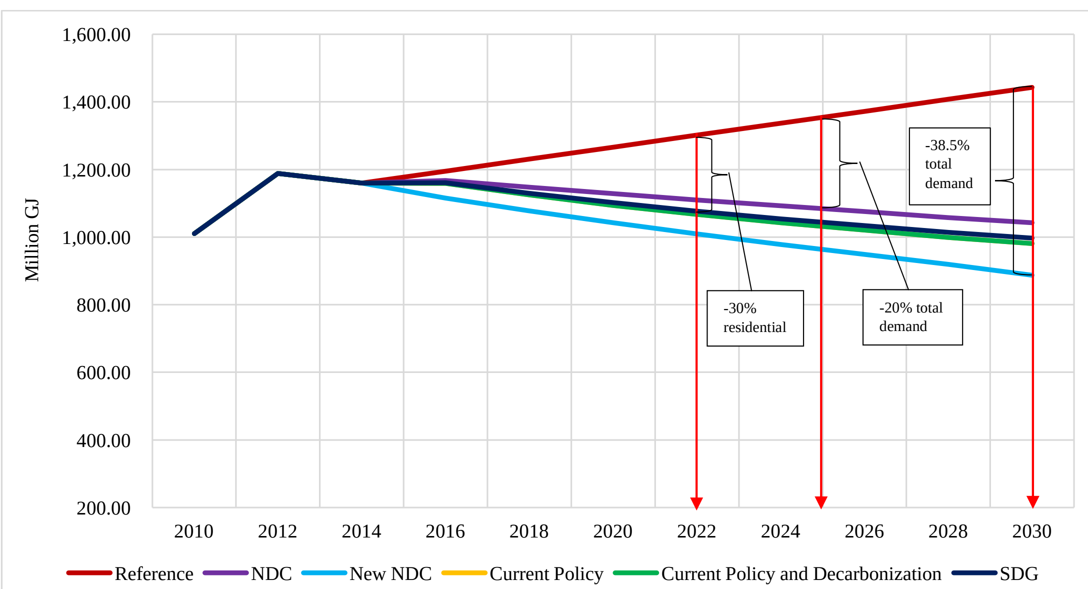

Figure 3. Total energy demand projection for scenarios

Current policy and current policy+decarbonization scenarios had the same demand value near 980 million GJ. Also, due to its extra energy requirement to meet goals, SDG scenario energy demand resulted higher than the current policy scenario and it was obtained approximately 997 million GJ by 2030. Finally, the NDC scenario has 20% reduction target from total demand by 2025 when current policy scenarios have a 30% reduction in the residential sector by 2022 and other sectors. This additional residential demand decrease in current policy scenarios results to lower total energy demand when it is compared to the NDC scenario.

In Chile, the reduction in energy demand depends on energy efficiency policies and measures as mentioned in Government´s action plans explicitly [56,60]. According to the energy efficiency action plan, the Chilean government set the goal of reducing Chile’s projected 2020 energy demand by 12% via energy efficiency programs by 2020 [60]. When the results of energy demand reduction were checked for each scenario, current policies and SDG scenarios showed reductions of 13.6% and 13.0%, accordingly when new NDC achieved 17.6% less demand than projected energy demand value for 2020. Moreover, the results showed that NDC demand reduction was obtained 10.8% less than projected value in 2020, which means that although new NDC, current policy and SDG scenarios met the target of 12% demand reduction by 2020 based on energy efficiency plan of the Chilean government, NDC scenario could not reach the target for 2020. If energy efficiency measures are well defined and planned based on energy sectors, energy demand reduction will still be realistic as occurred successfully in Denmark, Finland and Switzerland [73]. However, that kind of policies may require enough financial support internationally (as mentioned in NDC) and state budgets. Since the reduction is planned by the country, it should be ready financially.

Figure 4 presents the sectoral energy demand for each scenario in 2030 and base year 2015. The main results showed that transportation and industry dominated demand in all scenarios. When the base year 2015 and reference scenario 2030 results are compared, public, commercial, mining and industry sectors showed significant demand increase in 15 years. On the contrary, an increase in residential sector demand resulted vaguely. The demand decline in the residential sector at current policies can be seen clearly due to their specific efficiency targets when compared to the reference scenario and NDC scenarios. Although public, commercial and industry sectors show a declining trend for all scenarios compared to the reference scenario, the SDG scenario requires more energy by 2030 for those sectors in order to meet energy-related goals.

Also, mining and other industry sectors have major demand reduction in the new NDC scenario due to its considerable demand decrease in all sectors. The transportation sector, which is predominantly petroleum derivatives, follows a trend towards electric, hybrid, and more efficient vehicles. Although energy efficiency is applied in the transportation sector, it is still the dominant sector in energy consumption when compared with other sectors and its share reached 35% for NDC and new NDC scenarios, and 38% for current policy and SDG scenarios when it is obtained 32% for reference scenarios. Finally, it can be inferred that major energy savings can be achieved when a correct energy efficiency policy is implemented in the energy-intensive sectors of Chile.

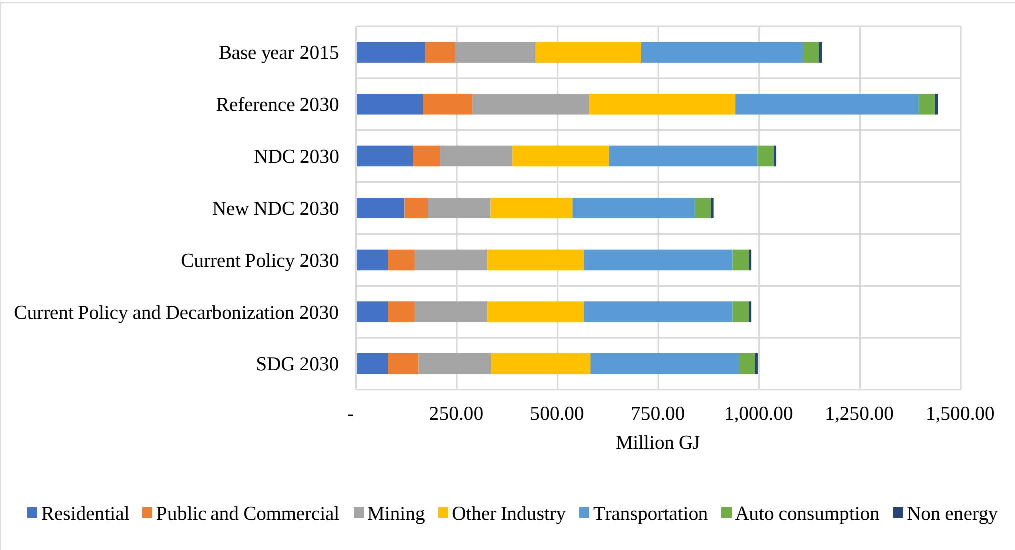

Figure 4. Sectoral energy demand for each scenario at 2030

In Figure 5, CO_2 emission (Million Metric Tonnes CO_2 Equivalent) of the scenarios are illustrated. As ~~summarized~~ summarised in Table 2, Chile declared 30% emission reduction by 2030 compared to 2007 in its NDC, which can increase up to 35-45% reduction with international support. Also, the new NDC scenario has 45% emission reduction target compared to 2016. After applying all strategies to each scenario, emissions are decided as a control mechanism to check if the scenario is meeting emission reduction or not. According to United Nations Framework Convention on Climate Change (UNFCCC) reports for Chile, CO_2 emission had the major share which was 74% in 2000 and 81% in 2016 (last reported year) between all greenhouse gas (GHG) emissions [71]. Due to its significant impact, CO_2 emissions are considered and compared in this study. The CO_2 emission (without land use, land-use change and forestry (LULUCF)) value for 2007 and 2016 in Chile were 62.46 and 87.44 million metric tonnes, accordingly [71]. Emission reductions compared to 2007 (CO_2 per GDP) for current policy, current policy+decarbonization, and NDC scenarios are calculated as 60.0%, 60.7%, and 51.8, respectively, which means that these scenarios are meeting at least 30% emission reduction target compared to 2007 value (CO_2 per GDP) in the scenario descriptions.

Also, new NDC and SDG scenarios have a 52.9% emission reduction when they are compared to 2016 value, that means they are also meeting their defined targets. Also, the important point is that the emission reduction difference between current policy and current policy + ~~decarbonization~~ decarbonization results from the extra phased out coal power plants in the ~~decarbonization~~ decarbonization scenario. Finally, it is interesting to mention that current policy and current policy+decarbonization scenarios also meet a 45% emission reduction target when compared to 2016 value, and they had 53.2% and 54.0% emission reduction, respectively. However, the NDC scenario only reduces 43.5% of total emissions compared to the 2016 values.

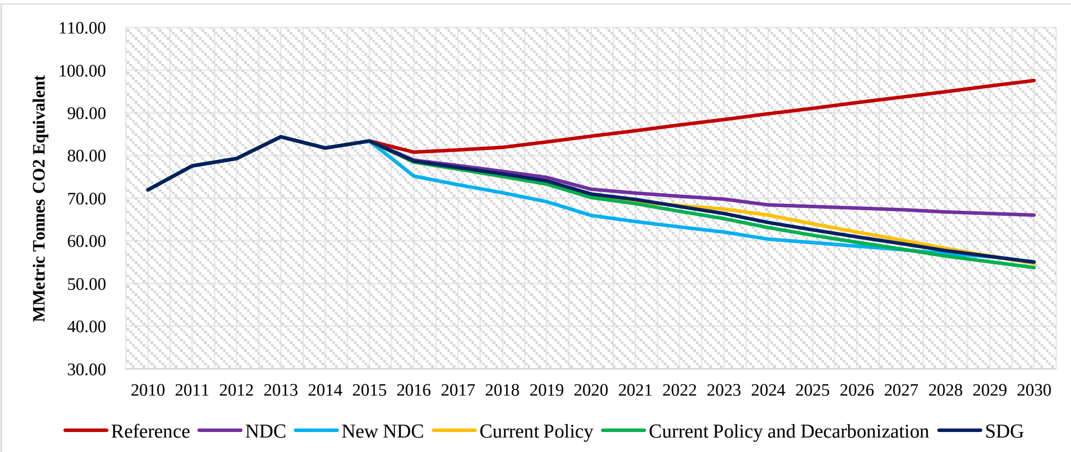

Figure 5. CO_2 emission without LULUCF (MMetric Tonnes of CO_2)

Although most of the scenarios meet the emission targets for 2030, it is important to ~~analyse~~ analyze the contribution of sectoral emissions. Figure 6 shows how many total emissions come from demand and transformation. Although the energy transformation sector contributes seriously to emission generation and policies have always been implemented to reduce emissions in the transformation sector, it is seen that emissions from the demand side have a considerable share. As shown in the figure, the majority of emissions in Chile tend to come from demand sectors. Almost 40% of total emissions come from the transformation (electricity generation) in 2015. Although emissions from the transformation sector show a significant reduction in different scenarios, the decrease in demand-side is observed slightly. However, due to its additional energy demand reductions from each sector to meet emission target (residential: 15%, P&C: 15%, mining: 15%, other industry: 15% and transport: 20%), new NDC scenario resulted in less contribution to CO_2 emissions in the demand side, which means demand-side policies in the new NDC scenario proved to be more successful in reducing emissions.

Also, when the contributions of main sectors in demand-side to CO_2 emissions are compared in Chile, all scenarios showed that the transport has the biggest share and it followed by industry, mining, public and commercial, and residential sector, accordingly. Therefore, in addition to implementing ~~decarbonization~~ decarbonization policies to reduce emissions from the transformation sector (mainly electricity production), appropriate energy efficiency and renewable energy policies should be developed and implemented for demand sides of transport, mining and other industries in Chile.

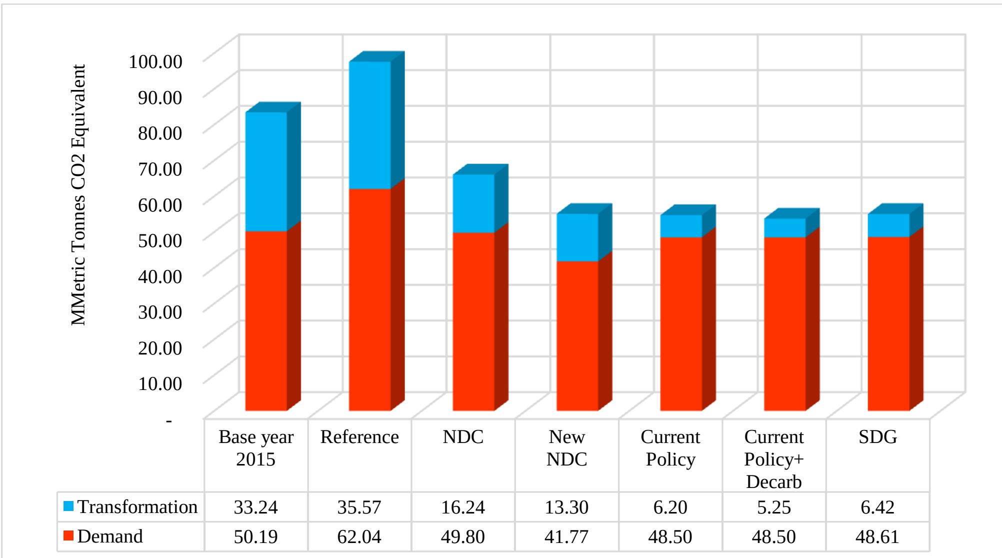

Figure 6. Emission comparison for scenarios by demand and transformation in 2030

In addition to the sectoral emission contribution, it is important to ~~analyse~~ analyze emissions by fuel for each scenario. Figure 7 presents demand-side CO_2 emission comparison of scenarios by fuels by 2030 and base year 2015. The reference scenario has the highest demand-side emission production, which is followed by the NDC scenario when new NDC has the lowest value near 40 million metric tonnes of CO_2 emissions. Due to having similar sectoral energy demand, current policy, current policy+decarbonization and SDG scenarios had the same emission results for demand-side near 50 million metric tonnes of CO_2. Diesel has the main contribution to emissions, and it is followed by gasoline, natural gas, LPG, jet kerosene, and oil. The emissions of diesel, jet kerosene and gasoline mainly come from the transport sector. Diesel usage of mining also has a direct contribution to emissions of the demand side. Also, the other industry sector has major consumption of oil, diesel, natural gas, LPG, and coal which contributes emissions.

Besides the demand-side CO_2 emission comparison of scenarios by fuels, the results of transformation side CO_2 emission comparison by fuels by 2030 are presented in Figure 8. In 2015, emissions in transformation sector come from coal (78.9%), natural gas (16.4%), and diesel (4.7%). Also, in the reference scenario, although it is assumed to use available diesel capacity as back up when necessary, not as the main production, it is seen that the emissions mainly come from coal (64.9%) and natural gas (35.1%). NDC, new NDC, current policy, current policy+decarbonization and SDG scenarios showed essential emission reduction in the transformation side due to implemented significant renewable energy generation priority to the model for these scenarios. Although emissions from coal are mostly dominant for each scenario, current policy+decarbonization and SDG scenarios showed slightly less emission from coal (49.6%) than natural gas (50. 4%). Finally, the coal emission difference in the transformation sector (1.16 million metric tonnes of CO_2) between current policy and current policy+decarbonization scenarios come from the phased-out coal power plants in the ~~decarbonization~~ decarbonization scenario by 2030.

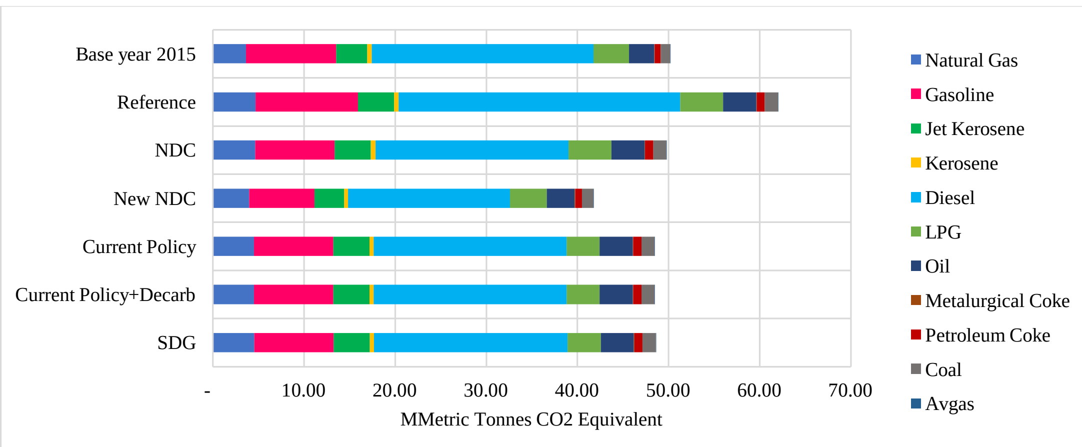

Figure 7. Demand-side CO_2 emission comparison of scenarios by fuels by 2030

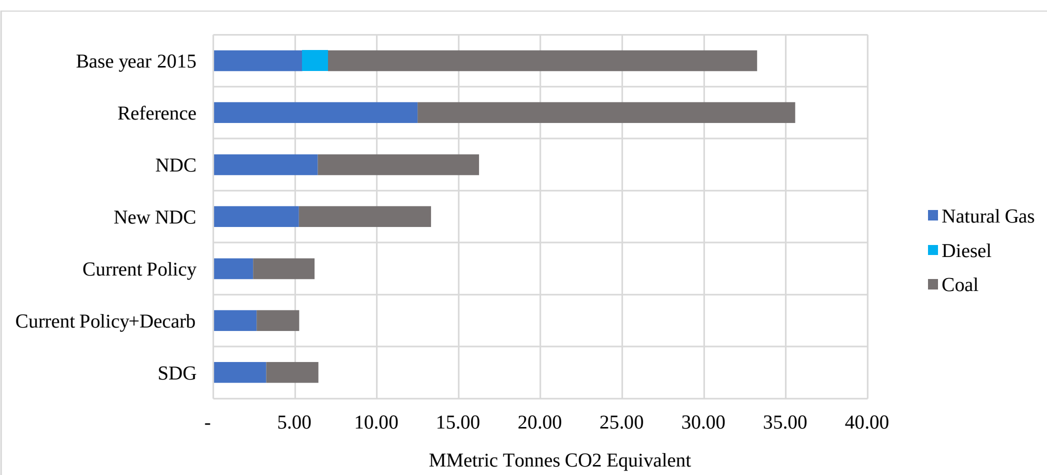

Figure 8. Transformation side CO_2 emission comparison of scenarios by fuels by 2030

Figure 9 shows the capacity projection for each scenario between 2010 and 2030. The reference scenario has only biomass, coal, diesel, gas, solar PV, hydro, wind and cogeneration power plants. Real installed capacity values were entered into the LEAP until 2018 for all scenarios.

Also, the capacity between 2018 and 2030 is increased based on the compound annual growth rate (CAGR) for the reference scenario, which follows historical capacity increase. Coal phase-out is not considered in the following scenarios: reference, NDC, new NDC, and current policy. In order to see the impact of ~~decarbonization~~ decarbonization only current policy+decarbonization and SDG scenarios include coal phase-out in the model. The Chilean government has planned to phase out 1047 MW of coal power plant capacity by 2024 and to get rid of all coal power plant by 2040. In addition to the plan by 2024, total coal capacity in current policy+decarbonization and SDG scenarios is reduced to 2500 MW by 2030. For the ~~decarbonization~~ decarbonization plan, natural gas and diesel capacities remained the same due to not having any phase-out plans for these fuels by the government. Also, it is assumed to use available diesel capacity as back up when necessary, not as the main production. However, if also natural gas phase-out contributes to the ~~decarbonization~~ decarbonization plan, coal capacity reduction can be smoother than current policy+decarbonization scenario which has approximately 2500 MW reduction since 2018. NDC and new NDC scenarios have a moderate increase in capacity of solar PV, wind and hydropower plants by 2024 as government plan [68] and until 2030 the capacities remained the same. However, in current policy, current policy+decarbonization, and SDG scenarios, capacity expansion plans are assumed with a significant share of solar PV, wind and hydropower plants by 2030 as well as solar CSP due to carbon taxes of USD 5/tCO_2 for fixed turbines or boilers above 50 MW_{th} in Chile [24,29].

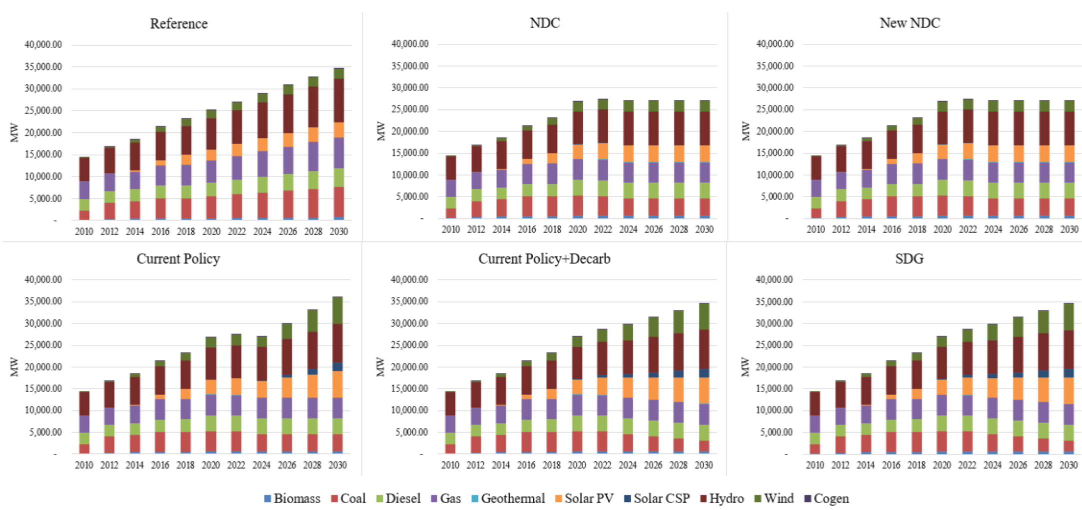

Figure 9. The capacity projection for each scenario between 2010 and 2030

Besides emission targets, renewable electricity generation percentage is mentioned in the scenarios as another target to compare. Figure 10 presents generation percentages by fuel and renewable energy share for each scenario in 2030. In order to maintain the balance between consumption and production in terms of power plant operations, base power plants have essential importance. Decommissioning of base power plants with high capacity such as coal and gas power plants may cause partial imbalances in the system in terms of supply reliability. For this reason, natural gas and a small amount of coal power plants are considered as base plants considering these imbalances in the establishment of scenarios.

Also, among the renewable energy sources, geothermal and hydropower plants are generally considered as base power plants. Accordingly, the contribution of hydropower plants to production as a base plant has been prioritized prioritized in the generated scenarios.

In 2015, electricity was mostly generated from coal, hydro and gas power plants and renewable generation share was 38%. The model results showed that the reference scenario has a similar fuel combination as the base year which is mostly fossil fuels, and renewable energy generation share is obtained 47% with the contribution of more solar PV and wind power production. In NDC and new NDC scenarios, electricity generation from fuels reduced to almost 40%, which met the scenario target "20% of the energy matrix in the generation is made up of unconventional renewable energies by 2025". Additionally, the current policy has the target of having 60% renewable electricity generation by 2035 [10,56]. When the target by 2030 is considered, it will be approximately 57-58% renewable electricity generation. As shown in the figure, current policy, current policy+decarbonization and SDG scenarios reached more than 80% renewable electricity generation by 2030 with or without decarbonizationdecarbonization. In current policy and decarbonization decarbonization scenarios, electricity generation is supplied from various resources and mostly renewable energies such as 28% wind, 25% solar PV, 17% hydro and, 13% solar CSP. Diversity in production, production from the country´s national resources and self-sufficiency are crucial elements to increase energy reliability and reduce external dependence in Chile.

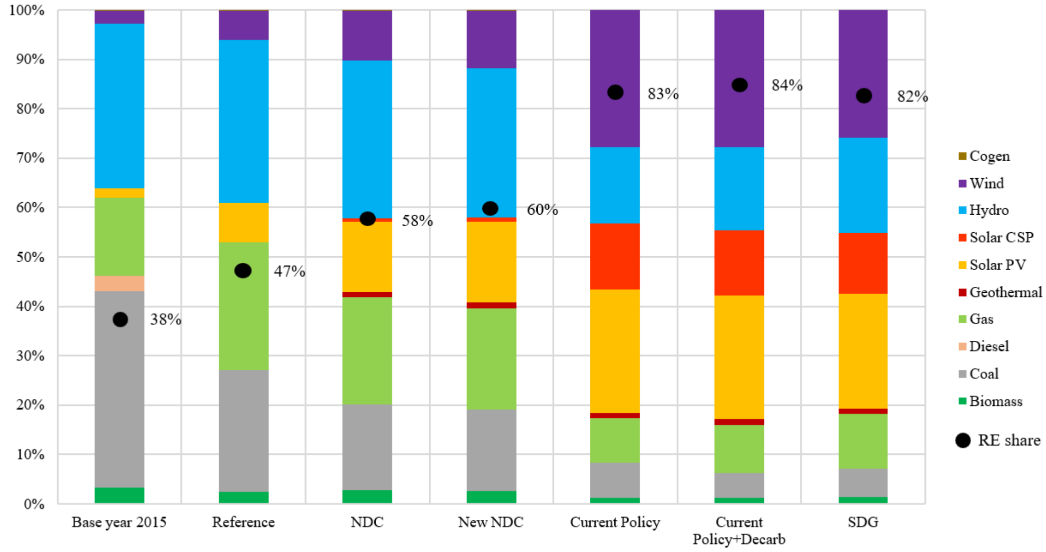

Figure 10. Generation percentage by fuel and renewable energy share for each scenario at 2030

When the current policy+decarbonizacion scenario is compared to the reference scenario, the production of decommissioned coal power plants is replaced with renewable energy (solar and wind) sources. Also, wind, PV solar, CSP solar and hydropower plants become more dominant and the main elements of electricity generation for current policy, current policy+decarbonizacion and SDG scenarios. Therefore, it shows that a cleaner production portfolio can be created with small amounts of fossil resources (gas or coal) and hydro as base power plants, and with more renewables, which results in fewer emissions and more diversification in terms of energy production.

Finally, the methodology followed in this paper can be adopted and reproduced for different countries contexts. When initial data sets including macroeconomic, demographic and energy balances are available for a country, the new model baseline can be replicated easily. Also, scenarios can be reproduced by considering the national and international commitments of other countries due to having their own NDC, SDG targets and current policy objectives.

5. Conclusion and policy implications

The aim of this study is creating a model to forecast energy demand and supply for Chile considering different policies by 2030, ~~analyzing~~ analyzing the impact of different policies (current policies, nationally determined contributions, sustainable development goals) and ~~decarbonization~~ decarbonization on energy planning in Chile by 2030, and evaluating the determined scenarios if they meet the defined targets. This work contributes to the literature by developing a long-term energy plan including all sectors for Chile, describing energy scenario alternatives and analysing analyzing national/international commitments such as nationally determined contributions and sustainable development goals.

The main findings of the study are as follows: due to its significant emission reduction target, the new NDC scenario has at least a 38.5% reduction in energy demand when it is compared to the reference scenario by 2030. Current policy and current policy+decarbonization scenarios had the same demand value near 980 million GJ. Also, due to its extra energy requirement to meet goals, SDG scenario energy demand resulted higher than the current policy scenario. NDC scenario has 20% of total energy demand reduction when the current policy has a 30% specific reduction in the residential sector and other main sectors as in NDC scenario. This additional residential demand decrease in current policy scenarios results in 6% lower total energy demand than the NDC scenario. Denmark, Switzerland and Finland showed an achievement on decoupling of economic growth from energy use, which means that economy is still growing while energy demand growth does not increase. After 2013, we observethe similar tendency is observed in Chile. For instance, energy use per capita decreased by 7.68% in 2014 and 8.93% in 2015, which means that GDP per capita was increasing while energy use per capita showed decreases after 2013 [73]. Therefore, when considering EU countries successful stories, international support and energy demand reduction trend of Chile after 2013, these reductions seem reasonable.

Emission decline for current policy, current policy+decarbonization, and NDC scenarios are obtained as 60.0%, 60.7%, and 51.8, which means that all scenarios are meeting at least 30% emission reduction target compared to 2007 value (CO_2 per GDP) in the scenario descriptions. Also, new NDC and SDG scenarios have a 52.9% emission reduction when they are compared to 2016 value, which means they are also meeting the 45% emission reduction target by 2030. However, NDC scenario did not achieve 45% emission reduction target by 2030.

Although the energy transformation sector contributes to emissions significantly and policies have mostly been implemented to reduce emissions in the transformation sector, the demand sector has a major contribution to the emissions in Chile when it is compared to the transformation sector. The results showed that even though emissions from the transformation sector demonstrate a significant reduction by 2030 in different scenarios, the decrease in demand side is not clearly noticed. The reference scenario has the highest demand-side emission production when NDC, new NDC, current policy, current policy+decarbonization and SDG scenarios showed essential emission reduction in the transformation side due to significant renewable energy generation priority in these scenarios. Finally, the coal emission difference in the transformation sector (1.16 million metric tonnes of CO_2) between current policy and current policy+decarbonization scenarios comes from the phased-out coal power plants in the decarbonization decarbonization scenario by 2030.

Current policy, current policy+decarbonization and SDG scenarios achieved more than 80% renewable electricity generation by 2030 with or without ~~decarbonization~~decarbonization. In current policy+decarbonization scenarios, electricity generation is supplied from various resources and mostly renewable energies such as 28% wind, 25% solar PV, 17% hydro and, 13% solar CSP. Generation mix, using the country´s national resources and self-sufficiency are vital aspects to increase energy reliability and reduce external dependency in Chile. When the current policy+decarbonizacion scenario is compared to the reference scenario, the production of phased-out coal power plants is substituted with renewable energy (solar and wind) sources. Also, wind, PV solar, CSP solar and hydraulic power plants become major plants of electricity generation for current policy, current policy+decarbonizacion, and SDG scenarios.

To ~~summarize~~summarise, the following should be considered by policy makers in Chile: a cleaner production portfolio can be created with small amounts of fossil resources (gas or coal) and hydro as base power plants, and with more renewables, which results in less emissions and more diversification in terms of energy production. Chile requires appropriate energy efficiency and renewable energy policies (with international support) to be implemented for demand sides of transport, mining, and industry sectors to reduce significant emissions at demand-side as it has ~~decarbonization~~ decarbonization plan for transformation side.

Finally, this study has some limitation due to the nature of the research methods applied and unavailable information. The study focuses on secondary data collection and literature reviews. All the analyses are shaped by the conditions of the country studied. This modelling approach is potentially limiting because it provides results for all Chilean energy sector, not regional analysis. Also, this study does not consider the sub-sectors of energy sectors in Chile and not having publicly available complete data sets. CO_2 emission without LULUCF is taken into account. Another limitation is weather impacts on electricity generation. In this study, LEAP could not consider weather impacts on renewable energy power plants such as hydroelectric, solar and wind. The current LEAP´s technology and emissions databases are also quite limited in scope.

There are some interesting research areas as future studies in energy modelling, and they are mentioned as follows: developing an energy model for Chile which ~~analyse~~ analyze the different regions separately (SEN, SEA, SEM), ~~realizing~~ realizing sensitivity analysis on developed scenarios, and adding to the model other technologies (such as battery storage system) not widely available today but that could play an important role in the future, to see their impact on the energy system in Chile.

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Abbreviations

CAGR	Compound annual growth rate
CO_2	Carbon dioxide
GHG	Greenhouse Gas Emissions
GJ	Gigajoule
GW	Gigawatts
LEAP	Long-range Energy Alternatives Planning System
LULUCF	Land Use, Land-Use Change and Forestry
MMetric	Million Metric
MW	Megawatts
NDCs	Nationally Determined Contributions
P&C	Public and Commercial
PV	Photovoltaics
RE	Renewable Energy
SEN	National Electricity System
SEA	Aysen Electricity System
SEM	Magallanes Electricity System
SDGs	Sustainable Development Goals
TED	Technology and Environmental Database
UNFCCC	United Nations Framework Convention on Climate Change
USD	US dollars

Appendix A.

Table A1:

ENERGY-RELATED SDGs		Indicator assessment for Chile 2030:	Energy Intensity (EI):	Energy requirement/savings to meet the target for Chile:
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture				
Target 2.1	Indicator 2.1.1: Prevalence of undernourishment	Data: 2000-2016 [74] CAGR: -1.20% Prevalence of undernourishment in 2030: 498,875.60 people	$EI = D_f * EC_f/(Eon_{farm} + Eoff_{farm})$ D_f = Country´s depth of food deficit = 90.25kcal*person^{-1}*day^{-1} [75] EC_f = The food energy content of cooked potato = 930.00 kcal/kg [76] $Eon_{farm,\ max}$ = On-farm agriculture energy usage= 0.005 GJ/kg [77] $Eoff_{farm,\ max}$ = Off-farm agriculture energy usage= 0.010 GJ/kg [77] EI (max)= 0.531 GJ/cap/year	*Assumptions: Total energy is calculated to nourish all people by 2030 and EI (max) is considered.* *E_required_total = 265,057.83 GJ* *This extra demand will impact other industry sector due to including agriculture.*
Goal 5. Achieve gender equality and empower all women and girls				
Target 5.b	Indicator 5.b.1: Proportion of individuals who own a mobile telephone	Data= 2016-2020 [78] CAGR= 1.18% Population without a mobile phone in 2030= 5,130,570.70 people	EI for owning a mobile phone[75,79]: $EI = E_b/t_h$ = ((16 kj/phone) / (27 hours)) * (24 h/day) * (1 phone /person) E_b=1.2 Ah (about 16 kJ) per phone t_h= 27 hours The energy intensity requirement for a mobile phone is estimated at 0.00519 GJ*cap^{-1}*year^{-1}	*The total energy requirement when all population own a mobile phone by 2030:* *E_required_total =26,627.66 GJ* *This additional demand will increase electricity demand in the residential sector.*
Goal 12. Ensure sustainable consumption and production patterns				
Target 12.3	Indicator 12.3.1: Global food loss index	Food losses in Latin America is cited approximately 220 kg/cap/year [80]. The targeted food loss (L_half) will be 110 kg/cap/year.	The energy intensity (EI) [75]: $EI = (EC_{storing} + EC_{retailing}) * L\_half$ EC_storing = Energy consumption for storing (MJ/kg) EC_retailing = Energy consumption for retailing (MJ/kg) L_half = Halving the losses based on target(kg/cap/year)	*E_required_total = 10,263,968.06 GJ* *It is assumed that this extra demand will impact on electricity use (for storage, processing, and packaging) of industrial and commercial sectors equally.*
Goal 13. Take urgent action to combat climate change and its impacts				
Target 13.1	Indicator 13.1.1: Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	The number of people displaced after the last three biggest earthquakes and tsunamis in Chile: 1,500,000.00 people in 2010, 970,000.00 people in 2014, and 1,000,000.00 people in 2015 [81,82]. The average number of people displaces is obtained approximately 1,156,666.67 people.	The average embodied final energy intensity to build a temporary, post-disaster container house is approximately 1.35 GJ*cap^{-1}*year^{-1} [75].	*Thus, the total energy requirement to replace affected people after the disaster in Chile is calculated:* *E_required_total =1,565,045.18 GJ* *The required energy is assumed to impact the construction and industrial sectors.*
Goal 17. Strengthen the means of implementation and ~~revitalize~~ revitalize the Global Partnership for Sustainable Development				

Target 17.6	Indicator 17.6.2: Fixed Internet broadband subscriptions per 100 inhabitants, by speed	Data= 2010-2017 [83]. CAGR= 7.96% between available years. The number of people without subscription in 2030= 12,454,704.18	The energy intensity to meet the target: 0.284–0.347 GJ/customer [75].	*When the average energy intensity is considered, the total energy requirement to meet this target (100% of the population with broadband subscription) for Chile is:* *E_required_total=3,927,715.51 GJ* *Telecommunication services belong to the commercial sector and it is assumed that this energy will impact the electricity demand of the commercial sector.*

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Comparison of Energy Scenario Alternatives for Chile: towards low-carbon energy transition by 2030

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Abstract

The objective of the paper is to generate an energy and environmental model using LEAP to forecast energy demand, supply, emissions for Chile by 2030 and create scenarios considering different policies motivated by current policy as well as national and international commitments from Chile. This paper contributes to literature by developing a long-term energy plan including all sectors for Chile, describing energy scenario alternatives and analyzing current policy, nationally determined contributions and sustainable development goals. Results indicate that scenarios with significant energy demand reduction for all sectors showed considerable emission reduction by 2030. In all scenarios, demand sector showed major contribution to emissions when compared to transformation sector. Although emissions from transformation sector demonstrate significant reduction by 2030, decrease in demand side is not clearly noticed for some scenarios. Chile requires appropriate energy efficiency and renewable energy policies for demand sides of sectors especially transport, mining and other industries to reduce emissions at demand-side as having decarbonization for transformation side. Scenarios including more wind, PVsolar, CSPsolar and hydropower plants reached more than 80% renewable electricity generation by 2030. Thus, cleaner production portfolio which results in fewer emissions and more diversification in terms of energy generation can be established in Chile.

Keywords: *Energy modelling, Scenario alternatives, Decarbonization, LEAP, NDCs, SDGs*

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1. Introduction

Climate change is one of the worldwide challenges for humanity in recent years. Human activities in the energy sector are vital to contributing greenhouse gas (GHG) emissions, which are mostly produced by fossil fuel combustion in, particularly, industry, transportation and electricity generation sectors [1]. Approximately 81% of global energy demand is met by fossil fuels including oil, coal, and gas [2]. Growing demand, tentative fuel price, and the rising concern about climate change are pushing countries to have long-term and sustainable energy planning. Therefore, many industrialized and developing countries have started to change their future energy plans towards decarbonization by analyzing several alternatives scenarios to see the impact of national and international commitments on energy plans [3]. In parallel to the developments in the world, Chile also began to take actions. After the Chilean Ministry of Energy was created in 2010, activities related to long-term energy planning have accelerated [4,5].

In the latest years, significant improvements in energy policy development can be observed in Chile [3]. MAPS-Chile can be considered as the first project that developed projections and mitigation action plans to reduce greenhouse gas emissions in Chile [6–8]. In 2014, the Energy Ministry of Chile decided to develop an agenda to define a new role for the Chilean government and the goals for future energy policy [9]. Energy Agenda 2050 was followed by The Road Map (Hoja de Ruta) and Energy 2050 studies which contained the key items of the long-term energy policy as promised in Energy Agenda [10]. In 2017, Chile ratified the Paris Agreement and committed to develop policies on climate change and to achieve sustainable development objectives. With this agreement, Chile proposed a target that represents a reduction of 30% in greenhouse gas (GHG) emissions below 2007 levels by 2030, and also to apply carbon taxes of USD 5/tCO_2 for fixed turbines or boilers above 50 MWth [11]. Besides international promises, Chile also set a national target to develop a long-term energy planning every five years for different energy scenarios that include expansion of generation and energy demand, in a horizon of at least thirty years [12]. After the elections in 2017, the new government announced Energy Route 2018-2022, in which the main axes of the new energy route were defined as follows: energy modernization, energy with a social seal, energy development, efficient transportation, low energy emissions, energy efficiency, and energy education and training [13]. Moreover, promoting renewable energy and energy efficiency were addressed as essential strategies for Chile to reduce emissions and reach its energy and environmental goals in various governmental studies [3].

Chile has divided into fifteen regions from north to south, and it has three main electricity grids: National Electricity System (SEN), the Aysen System (SEA), and the Magallanes System (SEM). Among these three grids, the National Electricity System includes thirteen regions and controls 99% of the total electricity supply of Chile [14]. The primary energy supply of Chile mainly consists of oil, coal, natural gas, biomass, hydro, and it has diversified in recent years with the inclusion of renewable energy such as solar, and wind sources. These sources are consumed in five main sectors in Chile: industry, mining, commercial and public, residential, and transport. Industry and transport represent the biggest shares in the total consumption of energy, and mining, which take place mostly in the northern regions of Chile [15,16], and presents heavily energy-intensive activities. Chile mainly depends on imported fuels for energy supply with an approximate proportion of 71% in 2017. Oil is the main energy source in the energy balance, and it is followed by biomass (mainly firewood), coal, natural gas, and hydro, respectively.

Chile has considerable renewable energy potential [3]. Especially, the north of Chile has the best worldwide solar energy potential for energy generation, on account of dryness and clear sky [17,18]. According to a joint study by the Ministry of Energy and the German Agency for International Co-operation in 2014, solar photovoltaic (PV) potential was estimated at 1263 GW, concentrated solar power at 548 GW, wind power at 37 GW (capacity factor of at least 30%), and small hydropower at 12 GW [19,20]. Additionally, it was projected that Chile has a potential of 164 GW from the ocean due to its long Pacific coast, 16 GW from geothermal sources due to containing 10% of the most active volcanoes in the world, and 1.4 GW from biomass sources [21].

After the national and international commitments of several countries in the latest years, studies in the field of energy modelling and planning increased in the literature. There are some recently published studies related to power generation and electricity expansion planning for Chile [22–29]. However, there is no published research about long-term energy planning, demand and supply forecasting or energy scenario alternatives for Chile including all energy sectors. Additionally, studies which analyze and compare national/international commitments such as nationally determined contributions (NDCs), current energy policies and sustainable development goals (SDGs) do not exist in the literature for Chile so far. Although some energy models including current policy and NDCs of countries exist in the literature, implementing sustainable development goals to the energy model is a significant novelty in terms of contribution to the literature.

Also, every country which ratified the Paris agreement has its own NDC target and sustainable development goals which reflect in its current energy policy. Therefore, the methodology followed in this research including energy modelling by considering NDC, SDGs and current policy can be applied to those countries and reproduced to create similar scenarios, and from that, the comparison can be developed to inform the policymakers about the progress and gaps.

Motivated by this gap in the literature, this research contributes to the state-of-the-art by generating energy and environmental model for Chile and analyzing different scenario alternatives which include energy strategies such as current policies, nationally determined contributions, sustainable development goals, and decarbonization. The contributions of this study to the literature can be listed as follows: 1) creating an energy model for all Chilean energy sector to forecast energy demand and supply by 2030 by using LEAP, 2) to analyze different policies, energy-saving potential and decarbonization impact on energy planning for alternative scenarios in Chile such as current policy, NDCs and SDGs, and 3) to evaluate and compare the determined scenarios if they meet their energy and environmental targets.

The reminder of the paper is organized as follows: Section 1 is an introduction to the paper which provides a background of the energy sector in Chile, relevance and objectives of the research, and contribution to the literature. Section 2 provides the methodology applied including a revision of long-term energy planning models and studies in the literature, modelling and scenarios for Chile. Section 3 presents and discusses in detail the results of the energy model work. Finally, section 4 is the conclusion of the analysis, and it proposes further research subjects.

2. Literature review

In order to choose a suitable modelling tool, energy system models and studies in the literature were reviewed. In the literature, although there are several categorizations for energy planning modelling, long-term energy planning approaches and models can be distributed into seven main categories, including simulation (e.g., RAMSES, BALMOREL, LEAP, WASP, etc.), scenario (e.g., MARKAL/TIMES, MESSAGE, LEAP, etc.), equilibrium (e.g., MARKAL, PRIMES, etc.), top-down (ENPEP-BALANCE, LEAP, etc.), bottom-up (HOMER, RAMSES, MARKAL/TIMES, MESSAGE, etc.), operation optimization (BALMOREL, MESSAGE, RAMSES, etc.), and investment optimization tools (MESSAGE, MARKAL/TIMES, RETScreen, etc.) as categorized in References [30,31].

In Table 1, some energy modelling studies obtained from literature in the last years were listed. Depending on the research objective, modelling can be done for all energy, just electricity, only demand or just one energy sector such as industry. As presented in the table, both developed (UK, Ireland, Taiwan) [32–34] and developing countries (Greece, Iran, Turkey, Ethiopia, Bangladesh, Pakistan, Indonesia, Colombia etc.) [30,35–40] were studied as a case study. In the last years, besides several LEAP studies, models which utilized TIMES, MARKAL, MESSAGE and some developed optimization models also exist in the literature. For instance, Amirnekooei et al. worked on several demand and supply-side management strategies including the utilization of electric stoves in place of natural gas-fuelled stoves, employment of coal power plants the utilization of hydro-pump storage and integrating gas turbine plants to combined-cycle ones for Iran by using LEAP. The results showed the natural gas and crude oil savings while considering these strategies in Iran [35]. Roinioti et al. studied Greece all energy system and developed scenarios by considering the different target of emission reduction and economic growth. The study presented that scenarios with high renewable energy penetration decrease CO_2 emissions while the capital cost is increasing [41]. Tsai and Chang investigated emission mitigation measures of Taiwan by 2030. The study included both technologies and tax measures. All sectors in Taiwan require to decrease energy intensities below the BAU scenario by 48% to 53% to meet its carbon reduction targets for 2050 [33]. Nieves et al. worked on demand and emission forecasting by considering the main energy sectors (industry, housing, and transport). Each sector studied separately based on scenarios including low-high economic growth and potential incentives for new technologies [39].

On the other hand, although any scientific study related to all energy sector modelling for Chile does not exist in the literature so far, there are some recently published studies related to power generation and electricity expansion planning for Chile [22–29]. Most of these studies are developed based on optimization models. For instance, Quiroga et al. worked on projections of the Chilean electric system's expansion without and with taxes, and demand growth estimation. The results showed that the availability of renewable energy capacity could improve the effectiveness of pollutant taxes. Verastegui et al. studied the Chilean power system expansion by 2040 by considering the government´s decarbonization plan. The research showed interesting results of the generation portfolio based on phasing out coal power plants by 2030, 2035 or 2040 [29]. O´Ryan et al. investigated renewable energy penetration on power expansion planning in Chile. CO_2 emissions of developed scenarios are obtained 10-15% less than business as usual scenario due to the significant share of renewables in the energy portfolio of developed scenarios [28].

In this study, LEAP was chosen as a modelling tool. LEAP is a software, developed by the Stockholm Environment Institute, Boston, to analyze energy demand and supply, energy policy, resource extraction, and accounting GHGs emissions [42]. LEAP has following advantages: permitting scenario analysis in terms of energy, environment and economy, having ability to follow energy consumption, production and resource extraction in all sectors, requiring less initial data input, providing a Technology and Environmental Database (TED) which offers up-to-date energy technologies data from a wide range of sources, affording data visualization for end-users [31], and finally being free of charge for academics and PhD students.

Table 1. Some energy modelling studies in the literature

Scenario approach	**Sector**	**Country**	***Model***	***Reference***
Renewable energy penetration in Crete's electric system	Electricity	Greece	*LEAP*	[43]
Resource planning integration	Energy	Iran	*LEAP*	[35]
Scenarios including uncertain aspects and technology options for clean energy usage	Energy	Greece	*LEAP*	[41]
Climate mitigation and global warming minimization potential	Electricity	Panama	*LEAP*	[44]
Sustainable energy scenario options to meet the challenges of both energy security and means of climate change mitigation	Energy	Ethiopia	*LEAP*	[36]

Energy efficiency and CO_2 mitigation potential in the industry sector	Energy in Industry sector	Turkey	*LEAP*	[45]
The impact of renewable energy, energy conservation and efficient technologies	Electricity	Bangladesh	*LEAP*	[37]
Renewables for energy security and carbon mitigation	Electricity	Indonesia and Thailand	*LEAP*	[46]
Moderate energy access, accelerate energy access policies, renewable energies promotion and energy efficiency policies	Energy (Demand)	Africa	*LEAP*	[30]
Renewable Energy Potential for Thailand's NDC	Energy (Demand)	Thailand	*LEAP*	[47]
Policy analysis including renewable energy clean coal, energy efficiency and conservation	Electricity	Pakistan	*LEAP*	[38]
Reduction targets for greenhouse gas emissions for 2020 and 2050	Energy	Ireland	*TIMES*	[48]
Climate and energy scenarios for 2050	Energy	Ireland	*TIMES*	[32]
Scenarios with different policies: CO_2 emission reduction constraint, renewable energy production targets etc.	Electricity	United Arab Emirates	*MARKAL*	[49]
Low carbon development roadmap	Energy	Taiwan	*MARKAL*	[33]
Emission reduction scenarios	Energy	UK	*MARKAL*	[34]
Energy technology options under different scenarios	Electricity	India	*MESSAGE*	[50]
Energy mix and nuclear option in Malaysia taking into account the national energy policies	Energy (Demand)	Malaysia	*MESSAGE*	[51]
Energy supply strategies by considering minimized the total system costs	Energy (Supply)	Syria	*MESSAGE*	[52]
New energy strategies introduced by the government including the nuclear power plant, hydropower and renewable energy	Electricity	Malaysia	*MESSAGE*	[53]
Scenarios with the lowest cost of generation and the lowest CO_2 emissions	Electricity	Indonesia	*Optimization Model*	[40]
Power system expansion planning under global and local emission mitigation policies	Electricity	Chile	*Optimization model*	[24]

Analyzing the energy demand and greenhouse gas emissions	Energy	Colombia	*LEAP*	[39]

3. Methodology

The methodological approach in this research is mainly based on a literature review, scenario description, scenario quantification, verification of model reliability, results and comparison, as illustrated in Figure 1. The literature review is explained in the previous section in order to give more information about energy modelling researches in the literature and energy/electricity studies about Chile. The following steps of the methodology are explained in additional detail within the following sections.

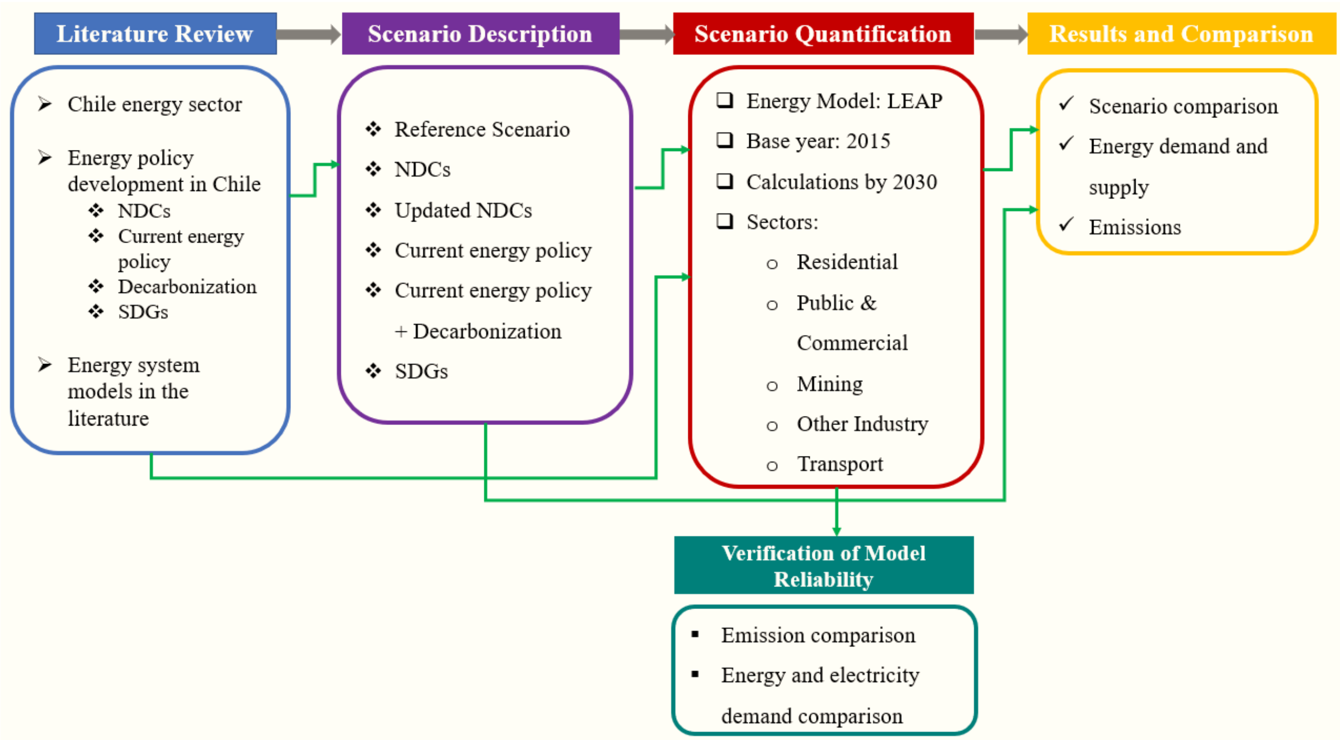


Figure 1. Flowchart of the methodological approach

3.1. Scenario description

The main step of the methodology is the scenario description in which each scenario was determined based on reviewed information. At this stage, current policy, current NDC, updated NDC, and decarbonization plans of Chile were reviewed from published international and government reports and these strategies were added to the scenarios. Additionally, the energy requirement to meet energy-related Sustainable Development Goals was investigated to make a further scenario in the model to compare to other scenarios. Finally, six different scenarios were determined as follows and the comparison of scenarios can be seen in Table 2:

Reference Scenario (Ref): This scenario takes into account the shift in the energy sector between 2008 and 2015 and calculates the energy sector estimates for 2030 according to this trend. It also ignores current policy, new policy, international and national promises by 2030.

Nationally Determined Contributions (NDCs) Scenario: This scenario considers some actions and targets of NDCs of Chile, which was presented to the United Nations Framework Convention on Climate Change in 2015 [3,11].This scenario considers 30% emission reduction by 2030, reduction of projected energy consumption, electricity demand growth for the transportation sector, renewable energy promotion, energy efficiency and no decarbonization as presented in Table 2.

New NDCs Scenario: In October 2019, Chile proposed an updated NDCs based on the previous promises. This scenario takes into account renewed NDCs which includes a 45% reduction in GHG when it is compared to 2016 [54]. In order to have considerable emission reduction, besides NDC, efficient usage of energy, biomass usage restriction in the residential sector, and significant energy demand reduction were considered in this scenario.

Current Policy Scenario: This scenario considers the last energy plan of the former government (Energy 2050) and the first energy plan of the new government of Chile (Route 2018-2022) [55,56]. Based on these plans, 30% emission reduction, 30% energy demand reduction in the residential sector, energy efficiency in major sectors, fossil fuels replacement with electricity, 57% electricity generation from renewable energy by 2030, fast improvement on transmission and distribution (T&D) lines, and restriction on biomass usage in the residential sector were considered.

Current Policy + Decarbonization Scenario: The government decided to start the process of decarbonization of the energy matrix through the preparation of a timetable for the withdrawal or reconversion of coal-fired plants. According to the decarbonization plan, all coal power plants will be phased out by 2040. Therefore, in this scenario, besides all requirements of the current policy, the new decarbonization plan of government which takes into account phasing out 1047 MW coal power plants by 2024 is also considered [55–57] and also additional coal phase-out in which coal power plant capacity is reduced to 2500 MW by 2030 is considered.

SDGs Scenario: Based on our previous study, Chile requires approximately 16,048,414.24 Gigajoules additional energy to meet energy-related SDGs, which increase energy demand by 2030. This scenario takes into account all current policies, decarbonization and also additional demand to meet energy-related Sustainable Development Goals (SDGs) by 2030. This extra energy demand impacts other industry, residential and commercial sectors as explained in Appendix A (TableA1).

Table 2. The summary of scenario description

	Reference Scenario	NDCs Scenario [58]	New NDCs Scenario [54]	Current Policy Scenario [55,56]	Current Policy + Decarbonization Scenario [55–57]	SDGs Scenario
Emission reduction *"It is a control mechanism to check if the scenario is meeting emission reduction."*	No emission reduction is considered.	30% emission reduction by 2030 compared to 2007. (with international support 35-45% reduction).	45% emission reduction by 2030 compared to 2016.	30% emission reduction by 2030 compared to 2007. (with international support 35-45% reduction).	30% emission reduction by 2030 compared to 2007. (with international support 35-45% reduction).	30% emission reduction by 2030 compared to 2007. (with international support 35-45% reduction).
Change in demand *"It refers to the demand changing in the scenario based on determined targets due to the energy efficiency of electricity or energy demand. "*	Not considered	20% reduction of projected energy consumption (total demand) by 2025. This reduction is realized by considering the reduction in the following sectors and fuels: - Residential: electricity and biomass share - P&C: electricity share - Mining: electricity and diesel share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share	Total 38.5% reduction of projected energy consumption (total demand) by 2030. This scenario includes energy demand decrease of NDC scenario and additional energy demand reductions from each sector to meet emission target as follows: Residential: 15% P&C: 15% Mining: 15% Other Industry: 15% Transport: 20%	Energy demand change in this scenario comes from 30% reduction from residential demand by 2022 and other sectors energy efficiency. Also, efficient usage of energy in major sectors are considered as NDC scenario. This reduction is realized by considering the reduction in the following sectors and fuels: - Residential: kerosene, LPG, electricity, natural gas, biomass share - P&C: electricity share - Mining: electricity and diesel share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share	Energy demand change in this scenario comes from a 30% reduction from residential demand by 2022 and other sectors energy efficiency. Also, efficient usage of energy in major sectors are considered as NDC scenario. This reduction is realized by considering the reduction in the following sectors and fuels: - Residential: kerosene, LPG, electricity, natural gas, biomass share - P&C: electricity share - Mining: electricity and diesel share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share	Energy demand change in this scenario comes from - The additional energy requirement to meet energy-related SDGs. - 30% reduction from residential demand by 2022. - Also, efficient usage of energy in major sectors are considered. This reduction is realized by considering the reduction in the following sectors and fuels: - Residential: kerosene, LPG, electricity, natural gas, biomass share - P&C: electricity share - Mining: electricity share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share

Transportation *"It considers any change in the transport sector due to electricity demand for EV or fossil fuel phase-out targets."*	Not considered	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) is decreased due to the increase of electricity share.	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) is decreased due to the increase of electricity share.	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) is decreased due to the increase in electricity share.	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) was decreased due to the increase in electricity share.	1.2% electricity demand increase per year is considered for the transportation sector [59]. Also, fossil fuels share (diesel and gasoline share) is decreased due to the increase in electricity share.
Capacity and Generation Mix *"It shows the change in the current electricity share portfolio by decreasing or increasing the current installed capacity."*	Real installed capacity and generation values were entered to the LEAP until 2018. Also, the capacity between 2018 and 2030 is increased based on the compound annual growth rate (CAGR).	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Finally, the capacity remained the same between 2024-2030. 20% of the energy matrix in the generation is made up of unconventional renewable energies by 2025.	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Finally, the capacity remained the same between 2024-2030. 20% of the energy matrix in the generation is made up of unconventional renewable energies by 2025.	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Moreover, additional capacities are added for solar PV, solar CSP, wind and hydro between 2024-2030. 57% of electricity generation from renewable energy by 2030. At least 50% of the fuels in the energy matrix should be low in GHG emissions and atmospheric pollutants.	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Moreover, additional capacities are added for solar PV, solar CSP, wind and hydro between 2024-2030. 57% of electricity generation from renewable energy by 2030. At least 50% of the fuels in the energy matrix should be low in GHG emissions and atmospheric pollutants. Decarbonization is realized based on governments plan by 2024 and an additional plan is considered by 2030 [29,57].	Real installed capacity and generation values were entered into the LEAP until 2018. Also, government´s capacity expansion plan is added to the scenario until 2024. Moreover, additional capacities are added for solar PV, solar CSP, wind and hydro between 2024-2030. 57% of electricity generation from renewable energy by 2030. At least 50% of the fuels in the energy matrix should be low in GHG emissions and atmospheric pollutants. Decarbonization is realized based on governments plan by 2024 and an additional plan is considered by 2030 [29,57].
Transmission and Distribution (T&D) Losses	Improvement in T&D losses are not considered	T&D losses are considered 4.5% by 2030 (Moderate improvement on T&D lines)	T&D losses are considered 4.5% by 2030 (Moderate improvement on T&D lines)	Historical growth is considered, and the losses reached 3.8% by 2030 (Fast improvement on T&D lines)	Historical growth is considered, and the losses reached 3.8% by 2030 (Fast improvement on T&D lines)	Historical growth is considered, and the losses reached 3.8% by 2030 (Fast improvement on T&D lines)

Fossil fuel transformation *"It addresses changing the total share of fossil fuel power plants in the current net generation. It can be executed by decommissioning the fossil fuel power plants installed capacity or using more clean fuels."*	No fossil fuel transformation is considered	Additional coal phase-out is not considered in this scenario.	Additional coal phase-out is not considered in this scenario.	Additional coal phase-out is not considered in this scenario.	1047 MW coal power plant capacity is phased out until 2024 (planned by the government) and also additional coal phase out is considered by 2030. Thus, total coal capacity is reduced to 2500 MW by 2030. Natural gas/diesel remained at the same capacity.	1047 MW coal power plant capacity is phased out until 2024 (planned by the government) and also additional coal phase out is considered by 2030. Thus, total coal capacity is reduced to 2500 MW by 2030. Natural gas/diesel remained at the same capacity.
Energy Efficiency (EE)	EE is not considered	EE is considered for all sectors. Biomass usage was restricted in the residential sector.	2020 EE action plan target is considered [60]. Biomass usage was restricted in the residential sector.	2020 EE action plan target is considered [60]. Biomass usage was restricted in the residential and other industry sector.	2020 EE action plan target is considered [60]. Biomass usage was restricted in the residential and other industry sector	2020 EE action plan target is considered [60]. Biomass usage was restricted in the residential and other industry sector

3.2. Scenario quantification

Scenario quantification was performed as the third step of the methodology by generating an energy model by using LEAP for the Chilean energy sector. The developed LEAP model for Chile includes historical energy sector data from 2008 and 2015, considers 2015 as the base year, and realize forecasting for 2030. The model includes five main energy sectors in Chile: residential, public and commercial (P&C), mining, industry and transportation. Also, non-energy usage and auto consumption sectors were added due to having in the national energy balances. Chile has almost 29% of the world's copper reserves, and it is the largest copper producer and exporter, having produced 37% of the world's copper in 2016 [19,61]. Thus, the mining sector was analyzed in the model separately from other industry sectors. The defined scenarios from the previous step were quantified and implemented to the developed energy model.

Figure 2 shows the structure of the LEAP model. LEAP requires demographic (population) and macroeconomic (GDP, sectoral GDP) data for the baseline of the model [42]. These data are used as inputs for demand analysis. Also, activity levels and energy intensity of each sector are required for demand analysis. In this study, activity level and energy intensities are assumed as listed in Table 3. The population was assumed as activity level for residential, public and commercial sectors when sectoral GDP shares were accepted as activity level for mining, industry and transportation sectors. Also, auto consumption and non-energy sectors mentioned in the energy balance were quantified with their total energy values in the model.

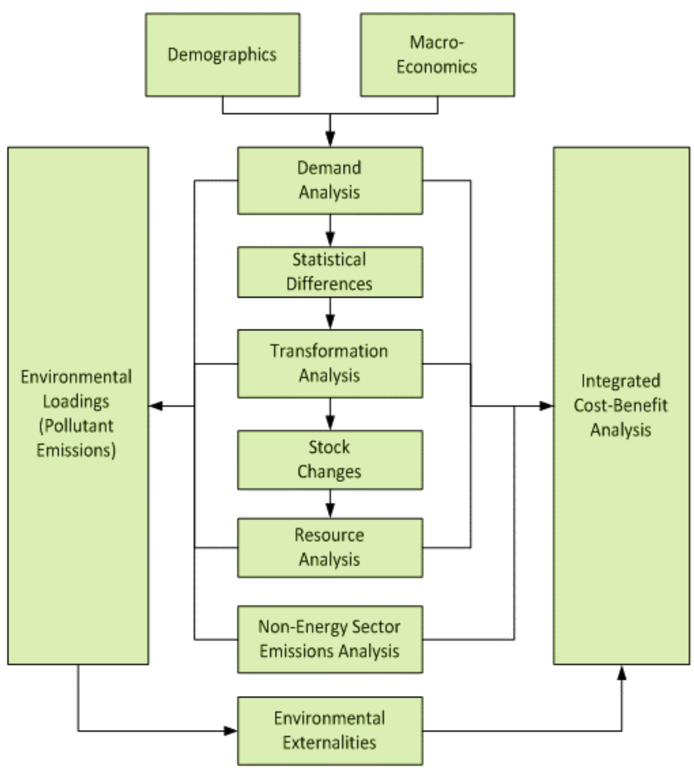


Figure 2. The structure of LEAP calculations [42]

Table 3. Activity level and energy intensity assumptions in the LEAP model

	Activity Level	Energy Intensity
Residential	Population (person)	$Energy_{total}$/Population (GJ/person)
Public and Commercial	Population (person)	$Energy_{total}$/Population (GJ/person)
Mining	GDP*Sectoral GDP share (US$)	$Energy_{total}$/Sectoral GDP (GJ/US$)
Industry	GDP*Sectoral GDP share (US$)	$Energy_{total}$/Sectoral GDP (GJ/US$)
Transport	GDP*Sectoral GDP share (US$)	$Energy_{total}$/Sectoral GDP (GJ/US$)
Auto consumption	Total Energy (Tcal, GJ)	
Non-energy	Total Energy (Tcal, GJ)	

Besides key assumptions such as demographics and macroeconomic data, LEAP requires historical energy demand and transformation data to forecast future values. Transformation analysis follows demand analysis as shown in Figure 2. It includes electricity generation, transmission and distribution losses of the system. For transformation analysis, technical parameters such as lifetime, efficiency, availability and cost values of power plants are required. The model is also suitable for emission analysis. LEAP allows generating several scenarios with the created model and compares the results based on energy and environmental outputs.

The equations considered in the LEAP model for energy demand, net energy consumption for transformation, carbon emissions from final energy consumption, and carbon emission from energy transformation are presented as follows [30,31,42].

Energy demand is a function of activity level and energy intensity for each sector, and it is calculated as Eq (1):

$$\mathrm{ED}_{b,s,t} = \mathrm{TA}_{b,s,t} * \mathrm{EI}_{b,s,t} \tag{1}$$

ED: energy demand (GJ)

TA: total activity (person or US$)

EI: energy intensity (GJ/person or GJ/US$)

Also, b is the branch, s is the scenario, and t is the year.

Additionally, the net energy consumption for transformation is calculated as Eq (2):

$$\mathrm{ET_p} = ETP_{sec,tec} * \left[\frac{1}{f_{p,\mathrm{sec,tec}}} - 1\right] \tag{2}$$

ET: net consumption for transformation (energy loss for a transformation process) (GWh)

ETP: product from the transformation process (GWh)

Also, f is energy transformation efficiency, tec is the technology, p is the type of primary energy, and sec is the type of secondary energy.

Moreover, the carbon emissions from final energy consumption are calculated from Eq (3):

$$\mathrm{CE}_{p,s,t} = \mathrm{TA}_{b,s,t} * \mathrm{EI}_{b,s,t} * \mathrm{EF}_{b,s,t} \quad (3)$$

CE: carbon emissions (MMetric Tonnes CO_2 eq)

$EF_{b,s,t}$: carbon emissions factor from the sector or branch b, scenario s and year t.

Finally, the emissions from energy transformation are calculated in LEAP as shown in equation 4:

$$\mathrm{CET} = ETP_{sec,tec} * \frac{1}{f_{p,\mathrm{sec},\mathrm{tec}}} * EF_{p,sec,tec} \quad (4)$$

CET: the carbon emission (MMetric Tonnes CO_2 eq)

$EF_{p, sec, tec}$: the emission factor from one unit of primary fuel type p, used to produce the secondary fuel type sec through the technology tec.

Relevant quantitative and qualitative information for modelling were gathered via scientific databases (Science Direct and Research Gate), open-access search engines (Google and Google Scholar), open access international organization reports, and publicly available Chilean governments´ reports. For instance, national energy balances are reported annually on the website of the National Energy Commission of Chile [62]. Demographic data are obtained from the National Statistics Institutes of Chile and the World Bank Group [63,64]. Macroeconomic data are taken from international statistic websites, Chilean government report and ministries publicly available documents [65–67]. Moreover, the required data for the transformation part of the model, such as power plant installed capacities and historical generation, are acquired from the reports and website of the National Energy Commission of Chile [68]. Technology and power plant information such as availability, efficiency are taken from published peer-reviewed articles, LEAP database, and international thesis [42,69,70]. Finally, emission impact data is taken from the available database in the LEAP model: Technology and Environmental Database [42].

To create a model in LEAP, users need to follow the basic structure and initial data sets explained as above. Required initial data (demographic, macroeconomic and energy balance data) can be obtained from national governmental and international institutions. This basic structure makes the model easier for reproducibility and replicability, and it enables the adoption of the LEAP model in various countries.

After quantifying all defined scenarios, the results including energy demand and supply, emissions for each scenario were compared, and the detailed results were given in the following section.

4. Results and Discussion

By using the collected and collated information, six scenarios with different strategies for a 15-year horizon have been obtained from the generated energy model. The main results are presented and compared in this section.

4.1. Reliability check for the energy model

Before presenting the results, the approach to check the accuracy of the model is also explained in this section. In order to verify the reliability of the created energy model, energy/electricity demand projections for 2030, and CO_2 emission values for base case are compared to published government reports and United Nations Framework Convention on Climate Change (UNFCCC) country emission reports.

Table 4 presents CO_2 emission (without LULUCF / LUCF) values obtained from UNFCCC and LEAP results for base years. In LEAP Chile model, 2015 is assumed as the base year of the model. And the first calculations are realized for the year 2016. In order to check the reliability of the model, emission values between 2010 and 2015 are calculated based on Technology and Environmental Database (TED) of LEAP and the difference between the real (UNFCCC values) [71] and calculated values (LEAP result) are presented in the table. LEAP results showed higher emission values with 3-5.5% error margin between 2010 and 2013. On the contrary, LEAP values are obtained lower than UNFCCC values with a 1.5-2.2% error margin for 2014 and 2015.

Table 4. CO_2 emissions (without LULUCF / LUCF) values obtained from UNFCCC and LEAP results for base case (MMetric Tonnes CO_2)

Year	UNFCCC values [71]	LEAP results	% error
2010	69.67	71.94	3.26%
2011	73.50	77.58	5.55%
2012	77.00	79.30	2.99%
2013	80.50	84.42	4.87%
2014	83.00	81.75	-1.51%
2015	85.30	83.43	-2.19%

Additionally, energy and electricity demand values are compared for LEAP reference scenario results and government´s national energy balances, as presented in Table 5. As mentioned above, 2015 is assumed as the base year and the model calculates the demand results for 2016 and beyond, that allows comparing real and calculated values. Reference scenario energy demand is obtained higher values than the values in 2016-2017 Chilean National Energy balances [15,72] with 0.23% and 0.27% error margin, accordingly.

Also, the calculated energy demand (LEAP reference scenario result) for 2030 is compared to government energy projection. Depending on the low, medium and high demand projection, the report indicated that energy demand for 2030 would vary between 350,000-400,000 Tcal [12]. When the low energy demand projection of government for 2030 is compared to LEAP result, -1.50% error margin is obtained for the calculated value. Finally, the projected and calculated electricity demand for 2030 are compared. The electricity demand for 2030 is obtained 95,388 GWh from LEAP when it was envisaged as 100,000-115,000 GWh depending on low, medium and high electricity demand scenarios [12]. When low electricity demand projection of government is compared to the calculated value, LEAP results showed lower demand value for electricity with a -4.61% error margin for 2030.

Table 5. Energy and electricity demand comparison for real and calculated values

Year	Energy Demand (Tcal)	LEAP energy demand results (Tcal)	Error (%)	Electricity Demand (GWh)	LEAP Electricity Demand (GWh)	Error (%)
2016	284,778 [15]	285,430	0.23%	-	-	-
2017	288,901 [72]	289,670	0.27%	-	-	-
2030	*350,000 (low)-* 400,000 (high) [12]	344,760	-1.50%	*100,000 (low)-* 115,000 (high) [12]	95,388	-4.61%

4.2. Comparison of scenarios

Figure 3 shows the total energy demand projection for all scenarios between 2010 and 2030. Without considering any policy for efficient use of energy, total energy demand will reach approximately 1450 million GJ as shown in the reference scenario. Other scenarios showed significant decreases due to having reduction targets on energy demand. NDC scenario is obtained as the second highest energy demand by 2030 although it has a 20% energy saving target by 2025. Due to its major emission reduction target, the new NDC scenario should have at least a 38.5% reduction in energy demand when it is compared to the reference scenario by 2030. Thus, the new NDC policy shows the lowest demand for 2030 which is 887 million GJ when it is compared to other scenarios.

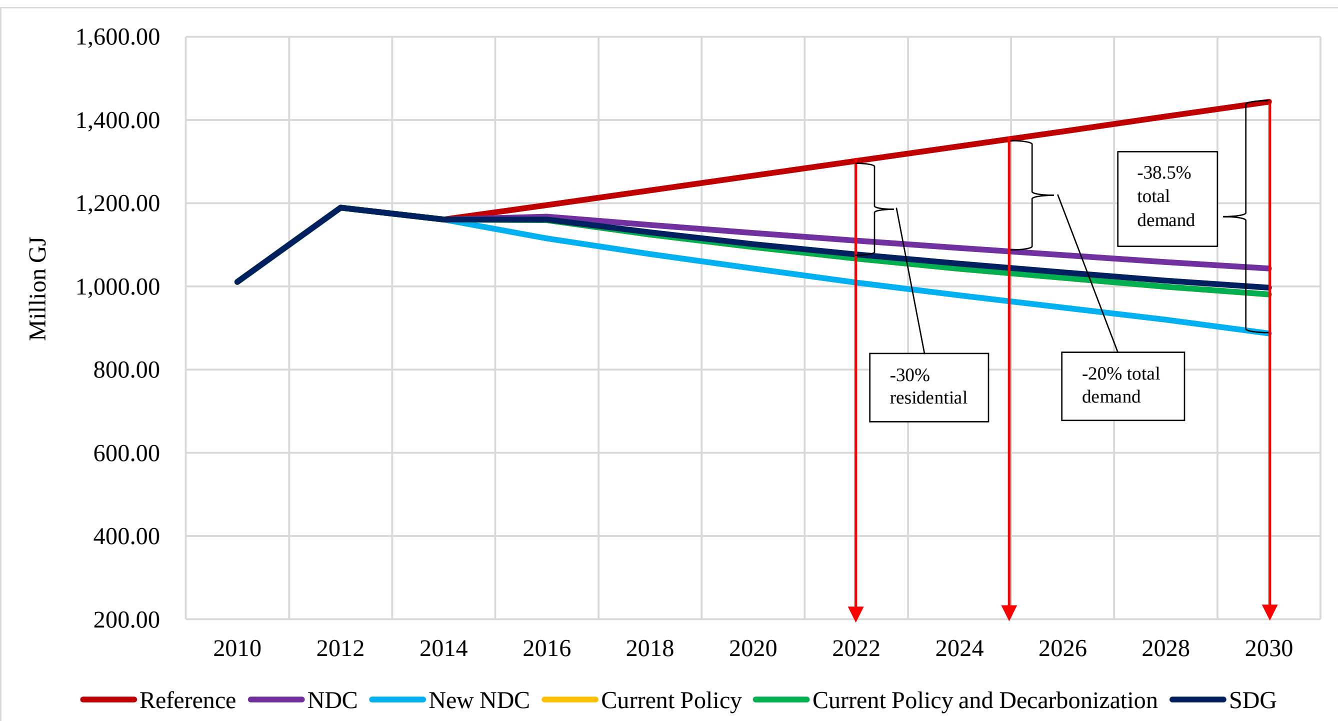


Figure 3. Total energy demand projection for scenarios

Current policy and current policy+decarbonization scenarios had the same demand value near 980 million GJ. Also, due to its extra energy requirement to meet goals, SDG scenario energy demand resulted higher than the current policy scenario and it was obtained approximately 997 million GJ by 2030. Finally, the NDC scenario has 20% reduction target from total demand by 2025 when current policy scenarios have a 30% reduction in the residential sector by 2022 and other sectors. This additional residential demand decrease in current policy scenarios results to lower total energy demand when it is compared to the NDC scenario.

In Chile, the reduction in energy demand depends on energy efficiency policies and measures as mentioned in Government´s action plans explicitly [56,60]. According to the energy efficiency action plan, the Chilean government set the goal of reducing Chile's projected 2020 energy demand by 12% via energy efficiency programs by 2020 [60]. When the results of energy demand reduction were checked for each scenario, current policies and SDG scenarios showed reductions of 13.6% and 13.0%, accordingly when new NDC achieved 17.6% less demand than projected energy demand value for 2020. Moreover, the results showed that NDC demand reduction was obtained 10.8% less than projected value in 2020, which means that although new NDC, current policy and SDG scenarios met the target of 12% demand reduction by 2020 based on energy efficiency plan of the Chilean government, NDC scenario could not reach the target for 2020. If energy efficiency measures are well defined and planned based on energy sectors, energy demand reduction will still be realistic as occurred successfully in Denmark, Finland and Switzerland [73]. However, that kind of policies may require enough financial support internationally (as mentioned in NDC) and state budgets. Since the reduction is planned by the country, it should be ready financially.

Figure 4 presents the sectoral energy demand for each scenario in 2030 and base year 2015. The main results showed that transportation and industry dominated demand in all scenarios. When the base year 2015 and reference scenario 2030 results are compared, public, commercial, mining and industry sectors showed significant demand increase in 15 years. On the contrary, an increase in residential sector demand resulted vaguely. The demand decline in the residential sector at current policies can be seen clearly due to their specific efficiency targets when compared to the reference scenario and NDC scenarios. Although public, commercial and industry sectors show a declining trend for all scenarios compared to the reference scenario, the SDG scenario requires more energy by 2030 for those sectors in order to meet energy-related goals.

Also, mining and other industry sectors have major demand reduction in the new NDC scenario due to its considerable demand decrease in all sectors. The transportation sector, which is predominantly petroleum derivatives, follows a trend towards electric, hybrid, and more efficient vehicles. Although energy efficiency is applied in the transportation sector, it is still the dominant sector in energy consumption when compared with other sectors and its share reached 35% for NDC and new NDC scenarios, and 38% for current policy and SDG scenarios when it is obtained 32% for reference scenarios. Finally, it can be inferred that major energy savings can be achieved when a correct energy efficiency policy is implemented in the energy-intensive sectors of Chile.

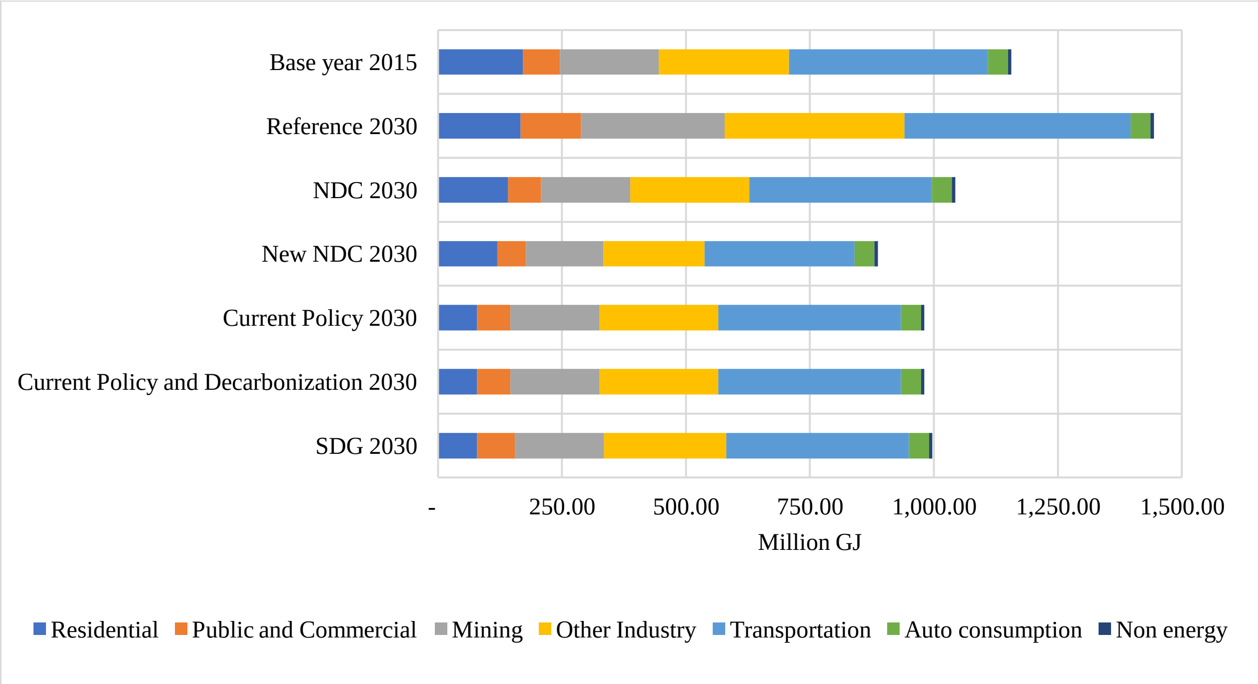


Figure 4. Sectoral energy demand for each scenario at 2030

In Figure 5, CO_2 emission (Million Metric Tonnes CO_2 Equivalent) of the scenarios are illustrated. As summarised in Table 2, Chile declared 30% emission reduction by 2030 compared to 2007 in its NDC, which can increase up to 35-45% reduction with international support. Also, the new NDC scenario has 45% emission reduction target compared to 2016. After applying all strategies to each scenario, emissions are decided as a control mechanism to check if the scenario is meeting emission reduction or not. According to United Nations Framework Convention on Climate Change (UNFCCC) reports for Chile, CO_2 emission had the major share which was 74% in 2000 and 81% in 2016 (last reported year) between all greenhouse gas (GHG) emissions [71]. Due to its significant impact, CO_2 emissions are considered and compared in this study. The CO_2 emission (without land use, land-use change and forestry (LULUCF)) value for 2007 and 2016 in Chile were 62.46 and 87.44 million metric tonnes, accordingly [71]. Emission reductions compared to 2007 (CO_2 per GDP) for current policy, current policy+decarbonization, and NDC scenarios are calculated as 60.0%, 60.7%, and 51.8, respectively, which means that these scenarios are meeting at least 30% emission reduction target compared to 2007 value (CO_2 per GDP) in the scenario descriptions.

Also, new NDC and SDG scenarios have a 52.9% emission reduction when they are compared to 2016 value, that means they are also meeting their defined targets. Also, the important point is that the emission reduction difference between current policy and current policy + decarbonization results from the extra phased out coal power plants in the decarbonization scenario. Finally, it is interesting to mention that current policy and current policy+decarbonization scenarios also meet a 45% emission reduction target when compared to 2016 value, and they had 53.2% and 54.0% emission reduction, respectively. However, the NDC scenario only reduces 43.5% of total emissions compared to the 2016 values.

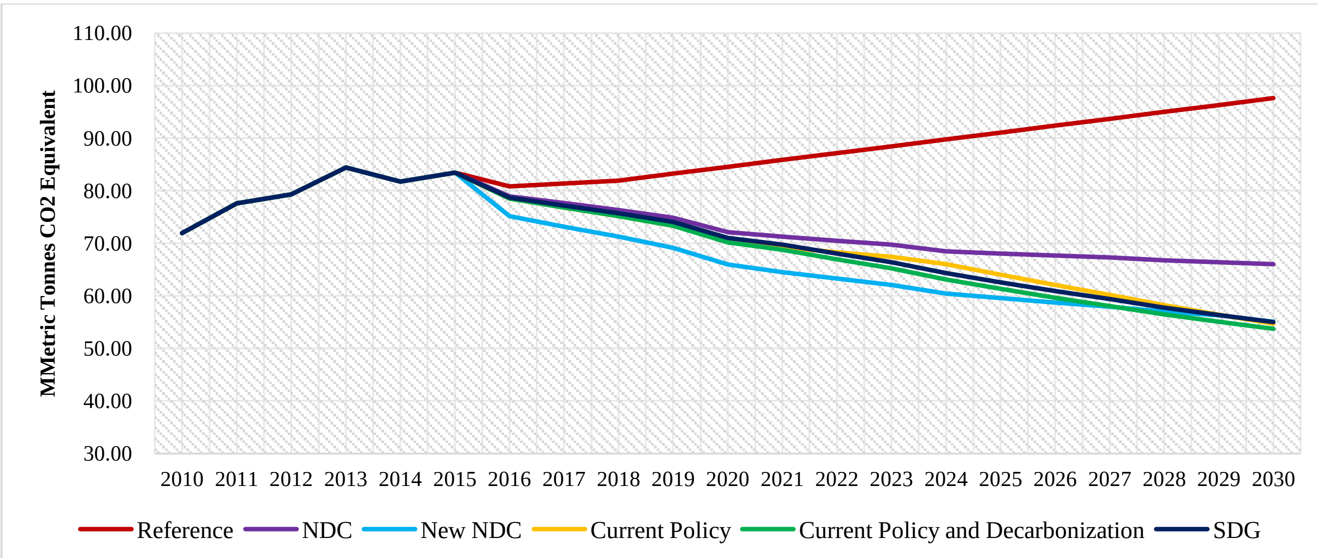
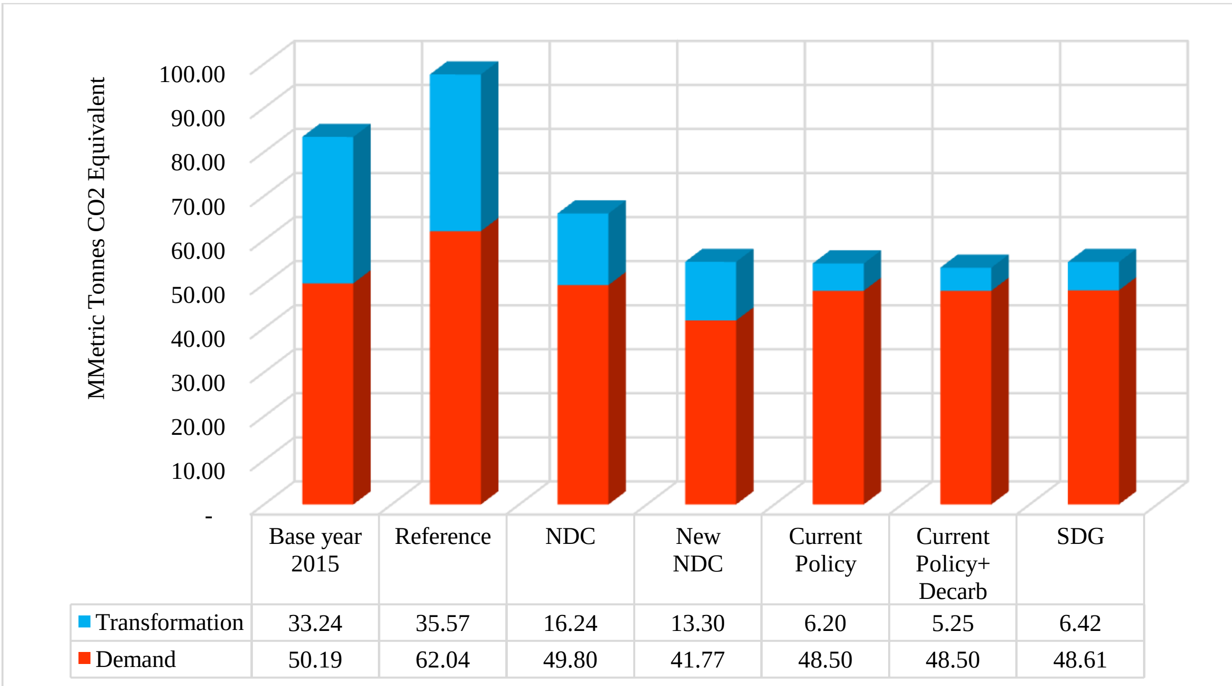


Figure 5. CO_2 emission without LULUCF (MMetric Tonnes of CO_2)

Although most of the scenarios meet the emission targets for 2030, it is important to analyze the contribution of sectoral emissions. Figure 6 shows how many total emissions come from demand and transformation. Although the energy transformation sector contributes seriously to emission generation and policies have always been implemented to reduce emissions in the transformation sector, it is seen that emissions from the demand side have a considerable share. As shown in the figure, the majority of emissions in Chile tend to come from demand sectors. Almost 40% of total emissions come from the transformation (electricity generation) in 2015. Although emissions from the transformation sector show a significant reduction in different scenarios, the decrease in demand-side is observed slightly. However, due to its additional energy demand reductions from each sector to meet emission target (residential: 15%, P&C: 15%, mining: 15%, other industry: 15% and transport: 20%), new NDC scenario resulted in less contribution to CO_2 emissions in the demand side, which means demand-side policies in the new NDC scenario proved to be more successful in reducing emissions.

Also, when the contributions of main sectors in demand-side to CO_2 emissions are compared in Chile, all scenarios showed that the transport has the biggest share and it followed by industry, mining, public and commercial, and residential sector, accordingly. Therefore, in addition to implementing decarbonization policies to reduce emissions from the transformation sector (mainly electricity production), appropriate energy efficiency and renewable energy policies should be developed and implemented for demand sides of transport, mining and other industries in Chile.



	Base year 2015	Reference	NDC	New NDC	Current Policy	Current Policy+ Decarb	SDG
Transformation	33.24	35.57	16.24	13.30	6.20	5.25	6.42
Demand	50.19	62.04	49.80	41.77	48.50	48.50	48.61

Figure 6. Emission comparison for scenarios by demand and transformation in 2030

In addition to the sectoral emission contribution, it is important to analyze emissions by fuel for each scenario. Figure 7 presents demand-side CO_2 emission comparison of scenarios by fuels by 2030 and base year 2015. The reference scenario has the highest demand-side emission production, which is followed by the NDC scenario when new NDC has the lowest value near 40 million metric tonnes of CO_2 emissions. Due to having similar sectoral energy demand, current policy, current policy+decarbonization and SDG scenarios had the same emission results for demand-side near 50 million metric tonnes of CO_2. Diesel has the main contribution to emissions, and it is followed by gasoline, natural gas, LPG, jet kerosene, and oil. The emissions of diesel, jet kerosene and gasoline mainly come from the transport sector. Diesel usage of mining also has a direct contribution to emissions of the demand side. Also, the other industry sector has major consumption of oil, diesel, natural gas, LPG, and coal which contributes emissions.

Besides the demand-side CO_2 emission comparison of scenarios by fuels, the results of transformation side CO_2 emission comparison by fuels by 2030 are presented in Figure 8. In 2015, emissions in transformation sector come from coal (78.9%), natural gas (16.4%), and diesel (4.7%). Also, in the reference scenario, although it is assumed to use available diesel capacity as back up when necessary, not as the main production, it is seen that the emissions mainly come from coal (64.9%) and natural gas (35.1%). NDC, new NDC, current policy, current policy+decarbonization and SDG scenarios showed essential emission reduction in the transformation side due to implemented significant renewable energy generation priority to the model for these scenarios. Although emissions from coal are mostly dominant for each scenario, current policy+decarbonization and SDG scenarios showed slightly less emission from coal (49.6%) than natural gas (50. 4%). Finally, the coal emission difference in the transformation sector (1.16 million metric tonnes of CO_2) between current policy and current policy+decarbonization scenarios come from the phased-out coal power plants in the decarbonization scenario by 2030.

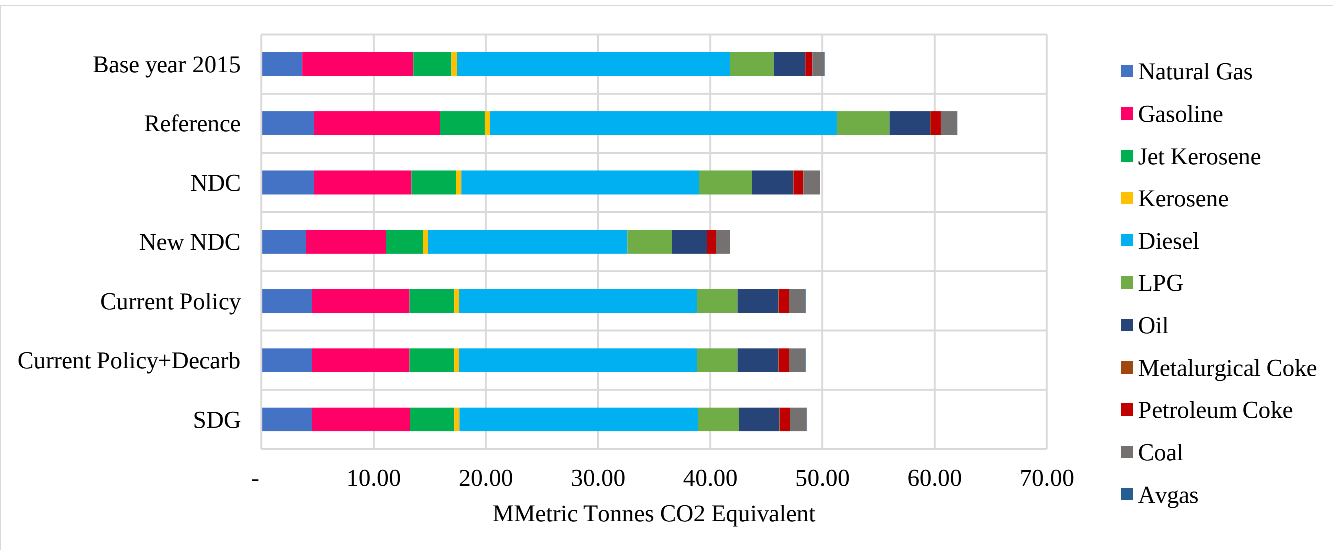


Figure 7. Demand-side CO_2 emission comparison of scenarios by fuels by 2030

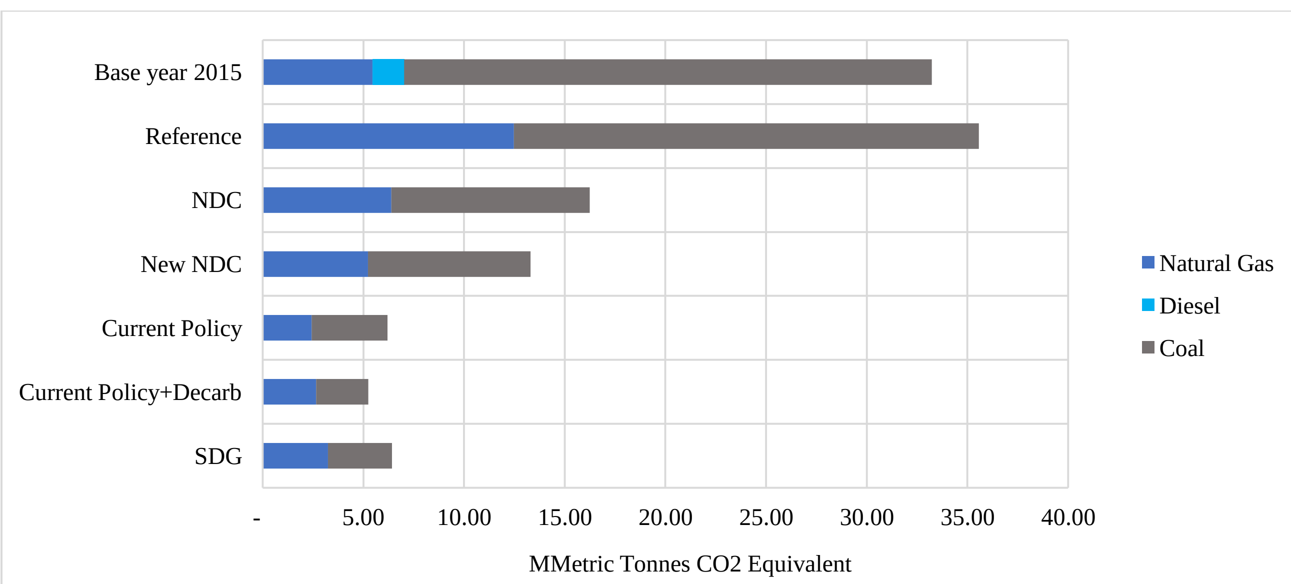


Figure 8. Transformation side CO_2 emission comparison of scenarios by fuels by 2030

Figure 9 shows the capacity projection for each scenario between 2010 and 2030. The reference scenario has only biomass, coal, diesel, gas, solar PV, hydro, wind and cogeneration power plants. Real installed capacity values were entered into the LEAP until 2018 for all scenarios.

Also, the capacity between 2018 and 2030 is increased based on the compound annual growth rate (CAGR) for the reference scenario, which follows historical capacity increase. Coal phase-out is not considered in the following scenarios: reference, NDC, new NDC, and current policy. In order to see the impact of decarbonization only current policy+decarbonization and SDG scenarios include coal phase-out in the model. The Chilean government has planned to phase out 1047 MW of coal power plant capacity by 2024 and to get rid of all coal power plant by 2040. In addition to the plan by 2024, total coal capacity in current policy+decarbonization and SDG scenarios is reduced to 2500 MW by 2030. For the decarbonization plan, natural gas and diesel capacities remained the same due to not having any phase-out plans for these fuels by the government. Also, it is assumed to use available diesel capacity as back up when necessary, not as the main production. However, if also natural gas phase-out contributes to the decarbonization plan, coal capacity reduction can be smoother than current policy+decarbonization scenario which has approximately 2500 MW reduction since 2018. NDC and new NDC scenarios have a moderate increase in capacity of solar PV, wind and hydropower plants by 2024 as government plan [68] and until 2030 the capacities remained the same. However, in current policy, current policy+decarbonization, and SDG scenarios, capacity expansion plans are assumed with a significant share of solar PV, wind and hydropower plants by 2030 as well as solar CSP due to carbon taxes of USD 5/tCO_2 for fixed turbines or boilers above 50 MW_{th} in Chile [24,29].

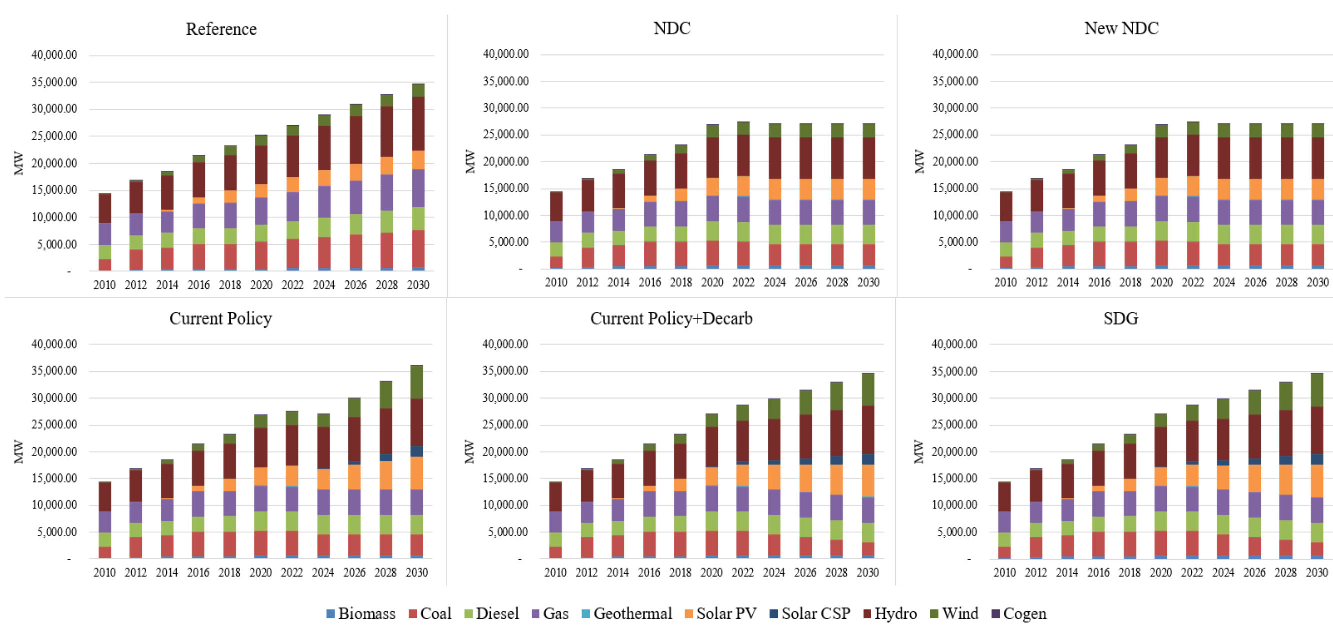


Figure 9. The capacity projection for each scenario between 2010 and 2030

Besides emission targets, renewable electricity generation percentage is mentioned in the scenarios as another target to compare. Figure 10 presents generation percentages by fuel and renewable energy share for each scenario in 2030. In order to maintain the balance between consumption and production in terms of power plant operations, base power plants have essential importance. Decommissioning of base power plants with high capacity such as coal and gas power plants may cause partial imbalances in the system in terms of supply reliability. For this reason, natural gas and a small amount of coal power plants are considered as base plants considering these imbalances in the establishment of scenarios.

Also, among the renewable energy sources, geothermal and hydropower plants are generally considered as base power plants. Accordingly, the contribution of hydropower plants to production as a base plant has been prioritized in the generated scenarios.

In 2015, electricity was mostly generated from coal, hydro and gas power plants and renewable generation share was 38%. The model results showed that the reference scenario has a similar fuel combination as the base year which is mostly fossil fuels, and renewable energy generation share is obtained 47% with the contribution of more solar PV and wind power production. In NDC and new NDC scenarios, electricity generation from fuels reduced to almost 40%, which met the scenario target "20% of the energy matrix in the generation is made up of unconventional renewable energies by 2025". Additionally, the current policy has the target of having 60% renewable electricity generation by 2035 [10,56]. When the target by 2030 is considered, it will be approximately 57-58% renewable electricity generation. As shown in the figure, current policy, current policy+decarbonization and SDG scenarios reached more than 80% renewable electricity generation by 2030 with or without decarbonization. In current policy and decarbonization scenarios, electricity generation is supplied from various resources and mostly renewable energies such as 28% wind, 25% solar PV, 17% hydro and, 13% solar CSP. Diversity in production, production from the country´s national resources and self-sufficiency are crucial elements to increase energy reliability and reduce external dependence in Chile.

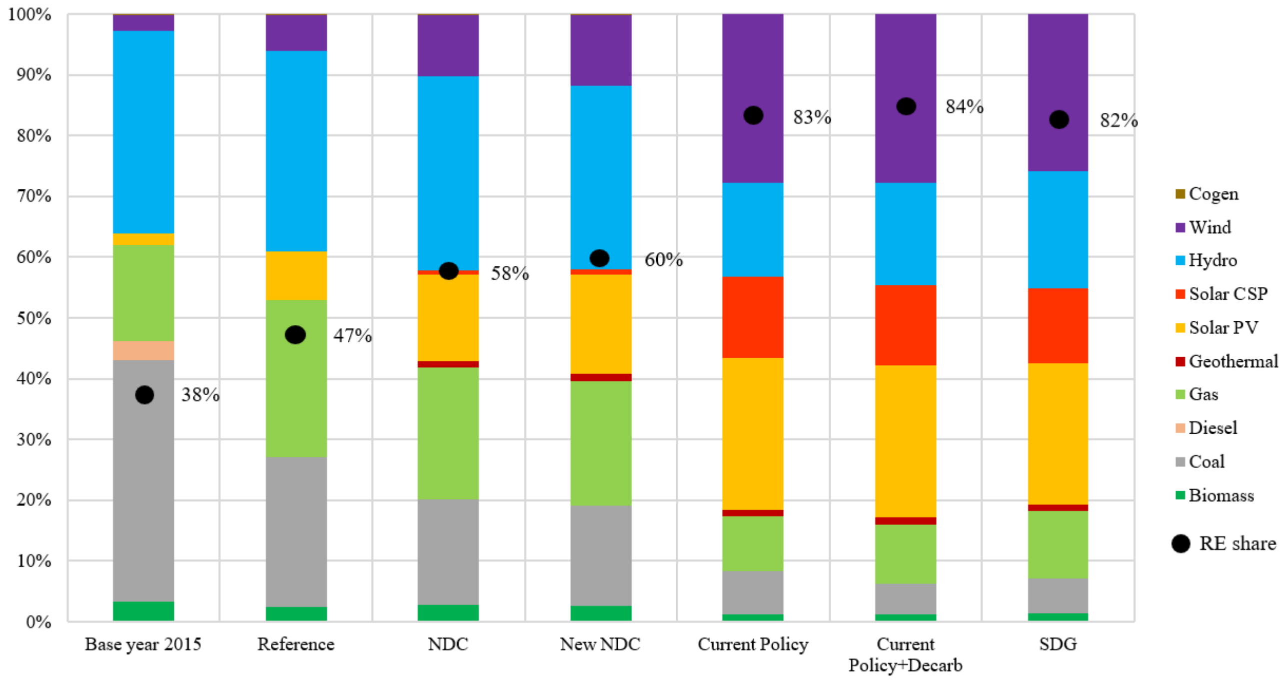


Figure 10. Generation percentage by fuel and renewable energy share for each scenario at 2030

When the current policy+decarbonizacion scenario is compared to the reference scenario, the production of decommissioned coal power plants is replaced with renewable energy (solar and wind) sources. Also, wind, PV solar, CSP solar and hydropower plants become more dominant and the main elements of electricity generation for current policy, current policy+decarbonizacion and SDG scenarios. Therefore, it shows that a cleaner production portfolio can be created with small amounts of fossil resources (gas or coal) and hydro as base power plants, and with more renewables, which results in fewer emissions and more diversification in terms of energy production.

Finally, the methodology followed in this paper can be adopted and reproduced for different countries contexts. When initial data sets including macroeconomic, demographic and energy balances are available for a country, the new model baseline can be replicated easily. Also, scenarios can be reproduced by considering the national and international commitments of other countries due to having their own NDC, SDG targets and current policy objectives.

5. Conclusion and policy implications

The aim of this study is creating a model to forecast energy demand and supply for Chile considering different policies by 2030, analyzing the impact of different policies (current policies, nationally determined contributions, sustainable development goals) and decarbonization on energy planning in Chile by 2030, and evaluating the determined scenarios if they meet the defined targets. This work contributes to the literature by developing a long-term energy plan including all sectors for Chile, describing energy scenario alternatives and analyzing national/international commitments such as nationally determined contributions and sustainable development goals.

The main findings of the study are as follows: due to its significant emission reduction target, the new NDC scenario has at least a 38.5% reduction in energy demand when it is compared to the reference scenario by 2030. Current policy and current policy+decarbonization scenarios had the same demand value near 980 million GJ. Also, due to its extra energy requirement to meet goals, SDG scenario energy demand resulted higher than the current policy scenario. NDC scenario has 20% of total energy demand reduction when the current policy has a 30% specific reduction in the residential sector and other main sectors as in NDC scenario. This additional residential demand decrease in current policy scenarios results in 6% lower total energy demand than the NDC scenario. Denmark, Switzerland and Finland showed an achievement on decoupling of economic growth from energy use, which means that economy is still growing while energy demand growth does not increase. After 2013, the similar tendency is observed in Chile. For instance, energy use per capita decreased by 7.68% in 2014 and 8.93% in 2015, which means that GDP per capita was increasing while energy use per capita showed decreases after 2013 [73]. Therefore, when considering EU countries successful stories, international support and energy demand reduction trend of Chile after 2013, these reductions seem reasonable.

Emission decline for current policy, current policy+decarbonization, and NDC scenarios are obtained as 60.0%, 60.7%, and 51.8, which means that all scenarios are meeting at least 30% emission reduction target compared to 2007 value (CO_2 per GDP) in the scenario descriptions. Also, new NDC and SDG scenarios have a 52.9% emission reduction when they are compared to 2016 value, which means they are also meeting the 45% emission reduction target by 2030. However, NDC scenario did not achieve 45% emission reduction target by 2030.

Although the energy transformation sector contributes to emissions significantly and policies have mostly been implemented to reduce emissions in the transformation sector, the demand sector has a major contribution to the emissions in Chile when it is compared to the transformation sector. The results showed that even though emissions from the transformation sector demonstrate a significant reduction by 2030 in different scenarios, the decrease in demand side is not clearly noticed. The reference scenario has the highest demand-side emission production when NDC, new NDC, current policy, current policy+decarbonization and SDG scenarios showed essential emission reduction in the transformation side due to significant renewable energy generation priority in these scenarios. Finally, the coal emission difference in the transformation sector (1.16 million metric tonnes of CO_2) between current policy and current policy+decarbonization scenarios comes from the phased-out coal power plants in the decarbonization scenario by 2030.

Current policy, current policy+decarbonization and SDG scenarios achieved more than 80% renewable electricity generation by 2030 with or without decarbonization. In current policy+decarbonization scenarios, electricity generation is supplied from various resources and mostly renewable energies such as 28% wind, 25% solar PV, 17% hydro and, 13% solar CSP. Generation mix, using the country´s national resources and self-sufficiency are vital aspects to increase energy reliability and reduce external dependency in Chile. When the current policy+decarbonizacion scenario is compared to the reference scenario, the production of phased-out coal power plants is substituted with renewable energy (solar and wind) sources. Also, wind, PV solar, CSP solar and hydraulic power plants become major plants of electricity generation for current policy, current policy+decarbonizacion, and SDG scenarios.

To summarise, the following should be considered by policy makers in Chile: a cleaner production portfolio can be created with small amounts of fossil resources (gas or coal) and hydro as base power plants, and with more renewables, which results in less emissions and more diversification in terms of energy production. Chile requires appropriate energy efficiency and renewable energy policies (with international support) to be implemented for demand sides of transport, mining, and industry sectors to reduce significant emissions at demand-side as it has decarbonization plan for transformation side.

Finally, this study has some limitation due to the nature of the research methods applied and unavailable information. The study focuses on secondary data collection and literature reviews. All the analyses are shaped by the conditions of the country studied. This modelling approach is potentially limiting because it provides results for all Chilean energy sector, not regional analysis. Also, this study does not consider the sub-sectors of energy sectors in Chile and not having publicly available complete data sets. CO_2 emission without LULUCF is taken into account. Another limitation is weather impacts on electricity generation. In this study, LEAP could not consider weather impacts on renewable energy power plants such as hydroelectric, solar and wind. The current LEAP´s technology and emissions databases are also quite limited in scope.

There are some interesting research areas as future studies in energy modelling, and they are mentioned as follows: developing an energy model for Chile which analyze the different regions separately (SEN, SEA, SEM), realizing sensitivity analysis on developed scenarios, and adding to the model other technologies (such as battery storage system) not widely available today but that could play an important role in the future, to see their impact on the energy system in Chile.

Acknowledgement

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Abbreviations

CAGR	Compound annual growth rate

CO_2	Carbon dioxide
GHG	Greenhouse Gas Emissions
GJ	Gigajoule
GW	Gigawatts
LEAP	Long-range Energy Alternatives Planning System
LULUCF	Land Use, Land-Use Change and Forestry
MMetric	Million Metric
MW	Megawatts
NDCs	Nationally Determined Contributions
P&C	Public and Commercial
PV	Photovoltaics
RE	Renewable Energy
SEN	National Electricity System
SEA	Aysen Electricity System
SEM	Magallanes Electricity System
SDGs	Sustainable Development Goals
TED	Technology and Environmental Database
UNFCCC	United Nations Framework Convention on Climate Change
USD	US dollars

Appendix A.

Table A1:

ENERGY-RELATED SDGs		Indicator assessment for Chile 2030:	Energy Intensity (EI):	Energy requirement/savings to meet the target for Chile:
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture				
Target 2.1	Indicator 2.1.1: Prevalence of undernourishment	Data: 2000-2016 [74] CAGR: -1.20% Prevalence of undernourishment in 2030: 498,875.60 people	$\mathrm{EI} = \mathrm{D_f} * \mathrm{EC_f}/(\mathrm{Eon_{farm}} + \mathrm{Eoff_{farm}})$ D_f = Country´s depth of food deficit = 90.25kcal*person^{-1}*day^{-1} [75] EC_f = The food energy content of cooked potato = 930.00 kcal/kg [76] $Eon_{farm, max}$ = On-farm agriculture energy usage= 0.005 GJ/kg [77] $Eoff_{farm, max}$ = Off-farm agriculture energy usage= 0.010 GJ/kg [77] EI (max)= 0.531 GJ/cap/year	*Assumptions: Total energy is calculated to nourish all people by 2030 and EI (max) is considered. E_required_total = 265,057.83 GJ* *This extra demand will impact other industry sector due to including agriculture.*
Goal 5. Achieve gender equality and empower all women and girls				
Target 5.b	Indicator 5.b.1: Proportion of individuals who own a mobile telephone	Data= 2016-2020 [78] CAGR= 1.18% Population without a mobile phone in 2030= 5,130,570.70 people	EI for owning a mobile phone[75,79]: EI =E_b/t_h = ((16 kj/phone) / (27 hours)) * (24 h/day) * (1 phone /person) E_b=1.2 Ah (about 16 kJ) per phone t_h= 27 hours The energy intensity requirement for a mobile phone is estimated at 0.00519 GJ*cap^{-1}*year^{-1}	*The total energy requirement when all population own a mobile phone by 2030: E_required_total =26,627.66 GJ* *This additional demand will increase electricity demand in the residential sector.*
Goal 12. Ensure sustainable consumption and production patterns				
Target 12.3	Indicator 12.3.1: Global food loss index	Food losses in Latin America is cited approximately 220 kg/cap/year [80]. The targeted food loss (L_half) will be 110 kg/cap/year.	The energy intensity (EI) [75]: $\mathrm{EI} = (\mathrm{EC_{storing}} + \mathrm{EC_{retailing}}) * \mathrm{L\_half}$ EC_storing = Energy consumption for storing (MJ/kg) EC_retailing = Energy consumption for retailing (MJ/kg) L_half = Halving the losses based on target(kg/cap/year)	*E_required_total = 10,263,968.06 GJ* *It is assumed that this extra demand will impact on electricity use (for storage, processing, and packaging) of industrial and commercial sectors equally.*
Goal 13. Take urgent action to combat climate change and its impacts				
Target 13.1	Indicator 13.1.1: Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	The number of people displaced after the last three biggest earthquakes and tsunamis in Chile: 1,500,000.00 people in 2010, 970,000.00 people in 2014, and 1,000,000.00 people in 2015 [81,82]. The average number of people displaces is obtained approximately 1,156,666.67 people.	The average embodied final energy intensity to build a temporary, post-disaster container house is approximately 1.35 GJ*cap^{-1}*year^{-1} [75].	*Thus, the total energy requirement to replace affected people after the disaster in Chile is calculated: E_required_total =1,565,045.18 GJ* *The required energy is assumed to impact the construction and industrial sectors.*
Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development				

Target 17.6	Indicator 17.6.2: Fixed Internet broadband subscriptions per 100 inhabitants, by speed	Data= 2010-2017 [83]. CAGR= 7.96% between available years. The number of people without subscription in 2030= 12,454,704.18	The energy intensity to meet the target: 0.284–0.347 GJ/customer [75].	*When the average energy intensity is considered, the total energy requirement to meet this target (100% of the population with broadband subscription) for Chile is:* *E_required_total=3,927,715.51 GJ* *Telecommunication services belong to the commercial sector and it is assumed that this energy will impact the electricity demand of the commercial sector.*

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Declaration of interests **04.05.2020**

I testify on behalf of all co-authors that:

- We wish to draw the attention of the Editor to the following facts which may be considered as potential conflicts of interest and to significant financial contributions to this work. [OR] We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome,
- This material has not been published in whole or in part elsewhere,
- After submitting Energy journal, the manuscript is not being considered for publication in another journal,
- All authors have been personally and actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content,
- The manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us,
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