PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING

LONG-TERM SUSTAINABLE ENERGY SCENARIOS MODELING AND ANALYSIS FOR CHILE: A ROADMAP TOWARDS 2030.

YELIZ SIMSEK

Thesis submitted to the Office of Graduate Studies in partial fulfillment of the requirements for the Degree of Doctor in Engineering Sciences.

Advisor:
RODRIGO ESCOBAR

Santiago de Chile, January 2020

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Dedicated to a better and sustainable world.

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CONTENTS

Pág.

LIST OF TABLES

LIST OF FIGURES

Pag.

NOMENCLATURE

AHP	Analytical hierarchy process
BAU	Business as usual
BNE	Balance Nacional de Energía
BP	British Petroleum
CAGR	Compound annual growth rate
CO_2	Carbon dioxide
Cap	Capita
EE	Energy Efficiency
EI	Energy intensity
ELECTRE	Elimination and choice translating reality
EU	European Union
FITs	Feed-in-Tariffs
GDP PPP/cap	Real GDP per capita
GDP	Gross Domestic Products
GHG	Greenhouse Gas Emissions
GJ	Gigajoule
GW	Gigawatts
Ha	Hectare
INDCs	Intended Nationally Determined Contributions
LEAP	Long-range Energy Alternatives Planning System
LULUCF	Land Use, Land-Use Change and Forestry
MADM	Multi-attribute decision-making
MAPS	Mitigation Action Plans and Scenarios
MAUT	Multi-attribute utility theory
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision method
MJ	Megajoule
MW	Megawatts

MODM	Multi-objective decision-making
Mtoe	Million tons of Oil Equivalent
NCRE	Non-conventional renewable energy
NDCs	Nationally Determined Contributions
NEB	National Energy Balance
NG	Natural Gas
OECD	Organization for Economic Co-operation and Development
PEI	Policy Effectiveness Indicator
PII	Policy Impact Indicator
PROMETHEE	Preference ranking organization method for enrichment evaluation
PV	Photovoltaic
R&D	Research and Development
RAI	Rural Access Index
RE	Renewable Energy
RBS	Required by Science
SDGs	Sustainable Development Goals
SEA	Aysen Electricity System
SEM	Magallanes Electricity System
SEN	National Electricity System
SIC	Central Interconnected System
SING	Northern Interconnected System
SWHs	Solar water heaters
TED	Technology and Environmental Database
TOPSIS	Technique for order preference by similarity to ideal solutions
TPES	Total Primary Energy Supply
UN	United Nations (UN)
USD	US dollars
UNFCCC	United Nations Framework Convention on Climate Change
WSM	Weighted sum method

PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

MODELOS Y ANÁLISIS DE ESCENARIOS DE ENERGÍA SUSTENTABLE A LARGO PLAZO PARA CHILE: UNA HOJA DE RUTA HACIA 2030.

Disertación enviada a la Dirección de Investigación y Postgrado en cumplimiento parcial de los requisitos para el grado de Doctor en Ciencias de la Ingeniería.

YELIZ SIMSEK

RESUMEN

Esta disertación se centra en la planificación de energía sustentable a largo plazo para Chile para 2030 y se desarrolló a través de cuatro artículos de revistas.

El objetivo principal de esta disertación es identificar una vía energética a largo plazo que satisfaga las necesidades energéticas de Chile de manera sustentable y cumpla con los objetivos energéticos nacionales e internacionales. En la búsqueda de este objetivo amplio, la investigación analiza la planificación de energía sustentable a largo plazo para Chile para 2030. El objetivo general de la tesis es investigar acciones/estrategias nacionales e internacionales para implementar la planificación de energía sustentable a largo plazo para Chile sistema nacional de energía para 2030 y compare los escenarios para lograr objetivos energéticos y ambientales futuros. Los objetivos específicos de esta disertación son: i) revisar el desarrollo energético, el potencial de recursos y las políticas actuales relacionadas en Chile (Articulo I), ii) evaluar la promoción de energía renovable y el análisis de políticas existentes hacia la descarbonización y la lucha contra el cambio climático (Articulo II), iii) evaluar los indicadores de los objetivos de desarrollo sustentable (ODS) relacionados con la energía y calcular los requisitos o ahorros de energía para cumplir los objetivos para 2030 en Chile (Articulo III), y iv) desarrollar un modelo energético y generar energía a largo plazo escenarios para Chile, incluido el escenario de referencia, la política energética actual, los objetivos de desarrollo sustentable, las contribuciones nacionales determinadas (NDC) y la descarbonización (Articulo IV).

El enfoque metodológico en esta investigación se basa en una revisión de la literatura, análisis de políticas actuales, evaluación de objetivos de desarrollo sustentable, descripción de escenarios, cuantificación de escenarios, desarrollo de modelos energéticos, resultados y comparación.

El presente trabajo está organizado en seis capítulos. El primer capítulo es la introducción. Los capítulos 2, 3, 4 y 5 responden al primer, segundo, tercer y cuarto objetivo específico de la disertación, respectivamente. Cada capítulo es una unidad autónoma y se puede leer sin la estricta necesidad de leer el resto de los capítulos.

La promoción de la energía renovable y la eficiencia energética son formas populares para que los países alcancen sus objetivos energéticos y ambientales y para la descarbonización y la descontaminación en la matriz energética futura.
La tecnología solar y eólica tuvo un mayor aumento de capacidad que la biomasa y mini hidro en los últimos años. Además, la capacidad de las tecnologías de energía solar fotovoltaica y eólica mostró un aumento significativo después de 2013. Las leyes relacionadas con la energía renovable implementadas entre 2012 y 2017 podrían tener el mejor impacto en la promoción de tecnologías de energía solar debido a sus PEI positivos.
La política legislativa "el objetivo importante para el aumento de la capacidad de energía renovable (70% del objetivo de instalación de energía renovable de nueva capacidad entre 2015 y 2050)" fue la mejor política entre todas las alternativas de políticas según la evaluación de los expertos.
Chile cumple dieciséis objetivos sin necesidad de ninguna intervención para 2030 entre veinticuatro objetivos de desarrollo sustentable relacionados con la energía. Como muestra el análisis, el objetivo 2.1, el objetivo 5.b, el objetivo 12.3, el objetivo 13.1 y el objetivo 17.6 requieren que se encuentre energía extra para 2030. Cuando se considera que todos los ODS se cumplen para 2030, se descubre que la demanda de energía para 2030 Los ODS se calcularon como 1,463.08 millones de GJ debido al requerimiento de energía adicional para cumplir con los ODS
Debido a su importante objetivo de reducción de emisiones, el nuevo escenario de NDC tiene una reducción de al menos 38.5% en la demanda de energía cuando se compara con el escenario de referencia para 2030.
El sector de la demanda tiene una contribución importante a las emisiones cuando se compara con el sector de transformación. Aunque las emisiones del sector de transformación demuestran una reducción significativa para 2030 en diferentes escenarios, la disminución de la demanda no se nota claramente. Por lo tanto, Chile también requiere la reducción de emisiones en el lado de la demanda, ya que tiene un plan de descarbonización para el lado de la transformación.
Los escenarios con una reducción significativa de la demanda de energía para todos los sectores mostraron una reducción considerable de las emisiones para 2030. En todos los escenarios, el sector de la demanda mostró una contribución importante a las emisiones en comparación con el sector de transformación. Aunque las emisiones del sector de transformación demuestran una reducción significativa para 2030, la disminución de la demanda no se nota claramente en algunos escenarios. Chile requiere políticas apropiadas de eficiencia energética y energías renovables para los sectores de demanda de los sectores, especialmente el transporte, la minería y otras industrias, para reducir las emisiones en el lado de la demanda como descarbonización para el lado de la transformación. Los escenarios que incluyen más plantas eólicas, fotovoltaicas, CSP solares e hidroeléctricas alcanzaron más del 80% de generación de electricidad renovable para 2030. Por lo tanto, se puede establecer una cartera de producción más limpia que resulte en menos emisiones y una mayor diversificación en términos de generación de energía en Chile.

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Thesis submitted to the Office of Graduate Studies in partial fulfilment of the requirements for the Degree of Doctor in Engineering Sciences by

YELIZ SIMSEK

SUMMARY

This dissertation focuses on long term sustainable energy planning for Chile by 2030 and it was developed through four journal papers.

The main objective of this dissertation is to identify a long-term energy pathway that would meet Chile´s energy need in a sustainable manner while meeting national and international energy targets. In pursuing this broad objective, the research analyzes the long-term sustainable energy planning for Chile by 2030. The overall objective of the thesis is to investigate national and international actions/strategies in order to implement to the long-term sustainable energy planning for Chilean national energy system by 2030 and compare the scenarios to accomplish future energy and environmental targets. The specific objectives of this dissertation are: i) to review energy development, resource potential and related current policies in Chile (Paper I), ii) to assess renewable energy promotion and existing policy analysis towards de-carbonization and combating climate change (Paper II), iii) to evaluate the indicators of energy-related sustainable development goals (SDGs) and calculate the energy requirement or savings to meet the targets for 2030 in Chile (Paper III), and iv) to develop an energy model and generate long-term energy scenarios for Chile including reference scenario, current energy policy, sustainable development goals, nationally determined contributions (NDCs) and decarbonization (Paper IV).

The methodological approach in this research is based on a literature review, current policy analysis, sustainable development goals evaluation, scenario description, scenario quantification, energy model developing, results and comparison.

The present work is organized into six chapters. The first chapter is the introduction. Chapter 2, 3, 4 and 5 answer to the first, second, third and fourth specific objective of the dissertation, respectively. Each chapter is an autonomous unity and can be read without the strict need for reading the rest of the chapters.

Promoting renewable energy and energy efficiency are popular ways for countries to reach their energy and environmental goals and for decarbonization and decontamination in the future energy matrix.

Solar and wind technology had more capacity increase than biomass and mini hydro in the latest years. Also, the capacity of solar PV and wind technologies showed significant increase after 2013. Renewable energy-related laws implemented between 2012 and 2017 could have the best impact on promoting solar energy technologies due to its positive PEIs. Legislative policy "the significant target for renewable energy capacity increase (70% of new capacity renewable energy installation target between 2015 and 2050)" was found the best policy between all policy alternatives according to experts´ assessment.
Chile meets sixteen targets without needing any interventions by 2030 between twenty-four energy-related sustainable development targets. As the analysis shows, Target 2.1, Target 5.b, Target 12.3, Target 13.1, and Target 17.6 require extra energy to be encountered by 2030. When all SDGs are considered to be met by 2030, it is found that energy demand for 2030 SDGs was calculated as 1,463.08 million GJ due to additional energy requirement to meet SDGs
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 the transformation sector. Although emissions from transformation sector demonstrate significant reduction by 2030, the 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, PV solar, CSP solar and hydro power 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.

Members of the Doctoral Thesis Committee:

Dr. Rodrigo Escobar
Dr. Gustavo Lagos
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Dr. Javier Bustos Salvagno
Dr. Amador Guzman
Dr. Tania Urmee

Santiago, January 2020

LIST OF PAPERS

The papers published, accepted or submitted during this PhD project as the principal author are listed below. The author of this dissertation executed the major work in writing these papers such as: creating methodology and models, simulations, interpretation of results and discussion.

This dissertation is based on the following journal papers, referred to in the text by their Roman numerals.

I. Yeliz Simsek, Álvaro Lorca, Tania Urmee, Parisa A. Bahri, Rodrigo Escobar "Review and Assessment of energy policy developments in Chile". *Energy Policy, Volume 127, April 2019, Pages 87-10.*

II. Yeliz Simsek, Tania Urmee, Álvaro Lorca, Wayan Santika, Parisa A. Bahri, Rodrigo Escobar "Evaluation of renewable energy deployment and policy analysis for Chile" (Submitted to *Renewable Energy* journal).

III. Yeliz Simsek, Wayan Santika, Anis Zaman, Tania Urmee, Parisa A. Bahri, Rodrigo Escobar "An analysis of energy requirement to meet Sustainable Development Goals" (Submitted to *Journal of Cleaner Production* journal).

IV. Yeliz Simsek, Hasret Sahin, Tania Urmee, Álvaro Lorca, Wayan Santika, Rodrigo Escobar "Comparison of energy scenario alternatives for Chile by 2030: towards low-carbon energy transition" *(Submitted to Energy journal)*

Moreover, the additional papers published, accepted or submitted during this PhD project as principal and co-author in several energy subjects are listed below.

I. Yeliz Simsek, Carlos Mata-Torres, Amador M. Guzmán, Jose M. Cardemil, Rodrigo Escobar “Sensitivity and Effectiveness Analysis of Incentives for Concentrated Solar Power Projects in Chile”. *Renewable Energy, Volume 129, Part A, December 2018, Pages 214-224.*

II. Yeliz Simsek, David Watts, Rodrigo Escobar “Sustainability Evaluation of Concentrated Solar Power (CSP) Projects under Clean Development Mechanism (CDM) by Using Multi Criteria Decision Method (MCDM)”. *Renewable & Sustainable Energy Reviews Journal, Volume 93, October 2018, Pages 421-438.*

III. Carlos Mata-Torres, Rodrigo A. Escobar, Jose M. Cardemil, **Yeliz Simsek**, Jose A. Matute “Solar polygeneration for electricity production and desalination: Case studies in Venezuela and northern Chile”. *Renewable Energy, Volume 101, February 2017, Pages 387-398.*

IV. Adriana Zurita, Armando Castillejo-Cuberos, Maurianny García, Carlos Mata-Torres, **Yeliz Simsek**, Redlich García, Fernando Antonanzas-Torres, Rodrigo A. Escobar “State of the art and future prospects for solar PV development in Chile”. *Renewable & Sustainable Energy Reviews Journal, Volume 92, September 2018, Pages 701-727.*

V. Marco Raugei, Enrica Leccisi, Vasilis Fthenakis, Rodrigo Escobar Moragas, **Yeliz Simsek** “Net energy analysis and life cycle energy assessment of electricity supply in Chile: Present status and future scenarios”. *Energy, Volume 162, 1 November 2018, Pages 659-668.*

VI. Caitlin Shem, **Yeliz Simsek**, Ursula Fuentes Hutfilter, Tania Urmee "Potentials and opportunities for low carbon energy transition in Vietnam: A Policy Analysis" *Energy Policy, Volume 134, November 2019, Article 110818.*

VII. Wayan G. Santika, Tania Urmee, **Yeliz Simsek**, Parisa A Bahri, M. Anisuzzaman "An assessment of energy policy impacts on the Sustainable Development Goals in Indonesia". (Submitted to *Renewable Energy* journal).

VIII. Nurcahyanto, **Yeliz Simsek**, Tania Urmee "Opportunities and Challenges in Developing Markets for Energy Service Companies (ESCOs) to Promote Energy Efficiency Programs in Indonesia". (Submitted to *Energy* journal).

IX. Wayan G. Santika, M. Anisuzzaman, **Yeliz Simsek**, Parisa A. Bahri, Tania Urmee, GM Shafiullah "Implications of the Sustainable Development Goals on national energy demand: The case of Indonesia". (Submitted to *Energy* journal).

Additionally, the author has published different conference papers, such as International and National congresses:

I. Yeliz Simsek, Carlos Mata-Torres, Jose M. Cardemil, Rodrigo Escobar “Incentives and Financial Conditions Effect Analysis on Levelized Cost of Electricity (LCOE) and Government Cost for Concentrated Solar Power (CSP) Projects in Chile”. *SolarPaces, AIP Conference Proceedings 2033 (1), 120005.*

II. Yeliz Simsek, Carlos Mata, Parisa A. Bahri, Tania Urmee, Rodrigo Escobar “Combination of solar incentives to have the best mechanism”. *2018 International Conference on Smart Green Technology in Electrical and Information Systems (ICSGTEIS), Pages 29-34.*

III. Yeliz Simsek, Rodrigo Escobar “Energy Demand Analysis and Policy Instruments Assessment for Mining Industry in Chile”. *ISES, SWC, Solar World Conference 4-7 November 2019, Santiago, Chile.*

1. INTRODUCTION

1.1. Context

The rising concern of climate change, high demand growth, and uncertain fuel price push countries to have long term, cost-effective, secure and sustainable future energy planning. According to BP Review of World Energy approximately 85 % of global energy demand is met by fossil fuels including oil, coal and gas (BP, 2016). If the usage of fossil fuels increases, the consequences will be irreversible on the environment. For the reasons mentioned above, many industrialized and developing countries started to change their future energy plans towards de-carbonization by setting some national and global targets to reduce emissions and increase the share of clean energy production technologies.

The Government of Chile was concerned about secure energy supply, sustainable development and environmental problems. Thus, in February 2017, Chile ratified the Paris Agreement and committed to develop policies on climate change and to achieve sustainable development objectives. In the scope of this agreement, Chile proposed a target which is a 30% GHG emission reduction below 2007 levels by 2030 and applying carbon taxes for fixed turbines or boilers above 50 MWth of USD 5/tCO_2 which will start in 2018 for 2017 emissions (The Committee of Ministers for Sustainability and Climate Change, 2015).

In addition to signing international agreements, Chile also set some targets at national level. According to the 83th article of the General Law of Electrical Services, modified by the Law Nº 20.936, every five years the Chilean Ministry of Energy will have to develop a long-term energy plan for different energy scenarios which include expansion of generation and energy demand, in a horizon of at least thirty years. These scenarios will be considered in the planning of an electrical transmission system (Ministerio de Energía, 2017). In 2016, the Chilean Ministry of Energy worked on long term energy and electricity demand and supply by considering essential targets for Chile's sustainable development until 2050 by considering four important pillars: quality and security of supply, energy as a driving force for development, environmentally-friendly energy, energy efficiency and energy education. According to this *Energy 2050* plan, some targets such as the electricity generation from renewable energy resources will reach at least 70% until 2050 (Comité Consultivo de Energía 2050, 2015; MINERGIA, 2015).

Besides several renewable energy resources, Chile has one of the best worldwide solar energy potential in the northern region for the energy generation on account of dryness and clear sky (Escobar et al., 2015, 2014). Industry in the north of Chile is based on heavily energy consumer mining activities. 99% of the electrical generation for the mining industry of the Northern Interconnected Power System is thermoelectric (Del Sol and Sauma, 2013). Although this specific condition, electricity generation from solar energy reached 3,4% until July 2017 according to National Energy Commission's monthly report (Comision Nacional de Energia, 2017). In order to meet the energy demand of several sectors such mining industry, to reduce its dependence on fossil fuel and diminish GHG emission caused by fossil fuel usage, it is necessary to develop a sustainable energy planning by using renewable energy technologies in the north of the country. Energy planning attempts to determine the optimal combination of energy sources and technologies to meet given energy demand by considering country's specific conditions and essential policies.

1.2. Objectives

The main objective of this dissertation is to identify a long-term energy pathway that would meet Chile´s energy need in a sustainable manner while meeting national and international energy and emission targets. In pursuing this broad objective, the research identifies a Long-Term Sustainable Energy Planning for Chile by 2030. The overall objective of the thesis is to investigate national and international actions/strategies in order to implement to the long-term sustainable energy planning for Chilean national energy system by 2030 and compare the scenarios to accomplish future energy and environmental targets.

The specific objectives of this dissertation are:

i) To review energy development, resource potential and related current policies in Chile (Paper I).

ii) To assess renewable energy promotion and existing policy analysis towards de-carbonization and combating climate change (Paper II).

iii) To evaluate the indicators of energy-related sustainable development goals (SDGs) and calculate the energy requirement or savings to meet the targets for 2030 in Chile (Paper III).

iv) To develop an energy model and generate long-term energy scenarios for Chile including reference scenario, current energy policy, sustainable development goals, nationally determined contributions (NDCs) and decarbonization (Paper IV).

1.3. Hypothesis

This dissertation proves the hypothesis that *the energy planning, based on bottom up engineering approach, and taking into consideration aspects of several energy policy and* *strategies, can identify measures that lead to significant energy savings, lower final energy demand, lower CO_2 emissions, decrease dependence on foreign fuel imports and increase the usage of national renewable energy resources in Chile by 2030.*

1.4. Methodology

The methodological approach in this research is based on a literature review, current policy analysis, sustainable development goals evaluation, scenario description, scenario quantification, energy model developing, results and comparison as shown in the Figure1-1.

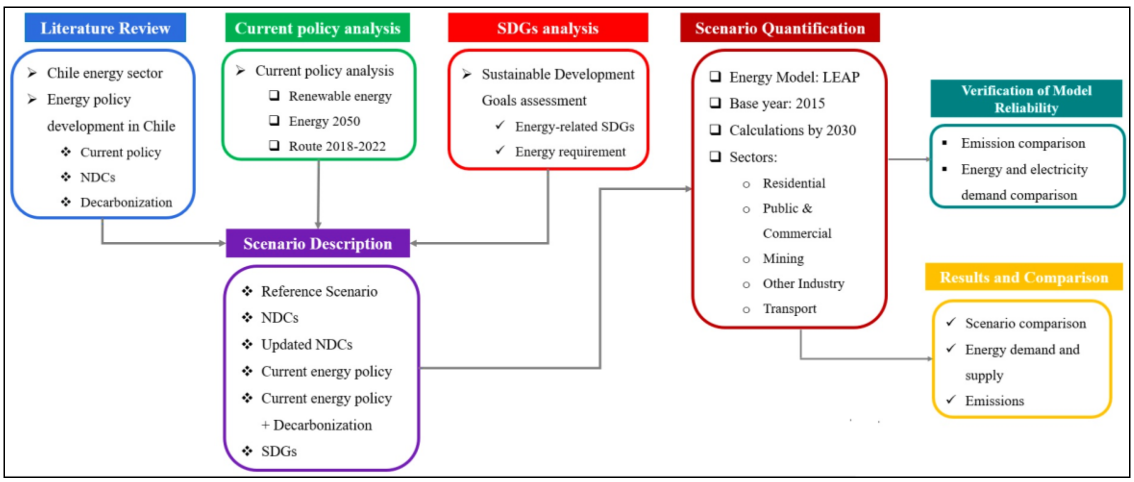


Figure 1- 1:Methodological approach of the dissertation

The literature review is the initial step in the methodology, where information about Chilean energy system, and energy policy development were collected and collated. This information was published as the first paper of this dissertation (Yeliz Simsek, Álvaro Lorca, Tania Urmee, Parisa A. Bahri, Rodrigo Escobar "Review and Assessment of energy policy developments in Chile". Energy Policy, Volume 127, April 2019, Pages 87-10).

In order to comprehend energy policy and renewable energy promotion in Chile, the detailed current energy policy analysis was realized as the second step of the methodology, and this research was submitted to Renewable Energy journal as the second paper of this thesis (Yeliz Simsek, Tania Urmee, Álvaro Lorca, Wayan Santika, Parisa A. Bahri, Rodrigo Escobar "Evaluation of renewable energy deployment and policy analysis for Chile").

Moreover, energy requirement to meet energy-related Sustainable Development Goals was studied as the third step of the methodology and they were investigated to make an additional scenario in the model to compare with other scenarios. This work is also submitted to the journal as the third paper of the dissertation (Yeliz Simsek, Wayan Santika, Anis Zaman, Tania Urmee, Parisa A. Bahri, Rodrigo Escobar "An analysis of energy requirement to meet Sustainable Development Goals" (Submitted to Journal of Cleaner Production journal)).

After current policy and sustainable development goal analyses; current NDC, updated NDC, decarbonization plans of Chile were reviewed from published government reports and these plans were also added to the scenarios as the fourth step of the methodology.

Finally, scenario quantification was done as the fifth step of the methodology by generating a model by using LEAP for Chilean energy sector which includes historical data from 2008 and 2015 and considers 2015 as base year. The model includes five main energy sectors in Chile: residential, public and commercial, mining, industry and transportation. The defined scenarios from the previous step were quantified and implemented to the developed model. Model development and scenario comparison are also combined and submitted to the journal as the last paper of the thesis to put together all work done during PhD study (Yeliz Simsek, Hasret Sahin, Tania Urmee, Álvaro Lorca, Wayan Santika, Parisa Bahri, Rodrigo Escobar "Comparison of energy scenario alternatives for Chile by 2030: towards low-carbon energy transition" (Submitted to Energy journal)).

1.5. Contents and research contributions

1.5.1. Contents

The present work is organized into six chapters. The first chapter is the introduction. Chapter 2, 3, 4 and 5 answer to the first, second, third and fourth specific objective of the dissertation, respectively. These chapters constitute each one of the research papers (journal paper I, II, III and IV) and contain the state of the art, the literature review, the methodology, the results, and the conclusions of this research within its scope. In this way, each chapter is an autonomous unity and can be read without the strict need for reading the rest of the chapters. Although this facilitates the reading of the document, it has the inevitable drawback of having to provide some redundant contents between the different chapters, especially in the introduction and the section of the different methodologies.

The content of each chapter is indicated as follow:

- In chapter 2, the research about "review and assessment of energy policy developments" is carried out to understand the energy sector in Chile. This chapter includes the published paper. This paper provides a broad overview of the energy sector and review of the Chilean energy policy development and environmental targets with emphasis on recent years. Finally, it also proposes an assessment of existing and required energy policy instruments for Chilean energy sectors by considering the promotion of renewable energy and energy efficiency and analyses the associated potential challenges.

- In chapter 3, the assessment of renewable energy promotion and existing policy analysis is carried out. Evaluation of renewable energy promotion and current policy analysis is vital to comprehend the current situation and to shed light on developing future policies. Motivated by this, this research aims to assess the renewable energy deployment in Chile and analyze current renewable energy policies by using a multi-criteria decision method (MCDM) in which the policy assessment criteria are weighed by Chilean energy experts. The objectives of this research are as follows: assessing the renewable energy deployment in Chile by considering global factors and current energy policies, developing a set of criteria to evaluate renewable energy policies and obtain criteria weights for policy assessment by expert opinions, and applying the Multi-Criteria Decision Analysis (MCDA) method to understand the energy policy preference and developments in Chile based on the chosen criteria.

- Chapter 4 includes research about sustainable development goals. Although Chile has promised on Nationally Determined Contributions under the Paris Agreement, there are no studies in the literature neither about meeting SDGs for Chile nor energy demand analysis to reach SDGs in Chile. Therefore, there is a need to understand the energy requirement or savings to meet the SDGs for Chile in order to be considered in long term energy planning. This paper aims to evaluate the indicators of energy-related SDGs and calculate the energy requirement or savings for each target when an intervention is needed to meet the target for 2030 in Chile.

- Chapter 5 contains the final research paper of this dissertation which collocates all researches done and includes energy model with generated scenarios. 1) to create a model to forecast energy demand and supply for Chile considering different policies by 2030, 2) to analyse the decarbonization impact on energy planning for different policies in Chile such as NDCs, current policy, and SDGs for Chile by 2030, 3) to evaluate the determined scenarios if they meet environmental and energy targets- Finally, chapter 6 concludes this dissertation.

1.5.2. Results

The results of this dissertation are explained in each chapter in details. Also, the main results are presented as follows:

- Promoting renewable energy and energy efficiency are popular ways for countries to reach their energy and environmental goals and for decarbonization and decontamination in the future energy matrix. Chile became successful in promoting renewable electricity production without fiscal incentives or FITs. Nevertheless, encouraging the mining and industry sector with obligatory regulations, using public finance for the residential sector, and mandatory economic instruments for the transport sector can be useful to increase the renewable energy share in all energy sectors (Chapter 2).
- Adoption of energy efficiency in several energy sectors is another substantial matter to achieve a sustainable energy future. Chile has mandatory energy efficiency labelling for appliances, energy codes, and efficiency standards for social housing and private residential buildings. However, there are no regulations for non-residential and commercial buildings and the efficient and clean use of firewood. In the Chilean industrial sector, only voluntary actions are found. In the transport sector, an energy efficiency label for new

light-duty vehicles has been mandatory since 2013. Chile has mostly voluntary support mechanisms for energy efficiency. Nonetheless, mandatory and economic support mechanisms are also necessary for specific sectors. More laws, regulations, codes, and standards must be implemented by the government in the industry, mining, and transport sectors to reach the national target. The combination of renewable energy instruments with energy efficiency instruments can produce a substantial impact (Chapter 2).

- Solar and wind technology had more capacity increase than biomass and mini-hydro in the latest years. Also, the capacity of solar PV and wind technologies showed a significant increase after 2013. Renewable energy-related laws implemented between 2012 and 2017 could have the best impact on promoting solar energy technologies due to its positive PEIs. Policies to promote wind and mini-hydro technologies could be less effective than solar energy due to having lower PEIs. Energy policy to promote biomass also seems insufficient with its irregular PEIs for different years. Additionally, PV and CSP technologies showed a significant reduction in LCOE in the last eight years due to technological developments (Chapter 3).

- Legislative policy “the significant target for renewable energy capacity increase (70% of new capacity renewable energy installation target between 2015 and 2050)” was found the best policy between all policy alternatives according to experts´ assessment. Under the monetary policy, solar subsidies for the residential sector was obtained as the best option. Finally, regulation for solar thermal technology had as the highest score between regulatory policy alternatives. Otherwise, a monetary policy about subsidizing pre-feasibility and pre-investment studies for renewables had the lowest overall score between all alternative policies, which means the experts do not find pre-feasibility incentives useful to promote renewables anymore (Chapter 3).

- Chile meets sixteen targets without needing any interventions by 2030 between twenty-four energy-related sustainable development targets. As the analysis shows, Target 2.1, Target 5.b, Target 12.3, Target 13.1, and Target 17.6 require extra energy to be encountered by 2030. When all SDGs are considered to be met by 2030, it is found that energy demand for 2030 SDGs was calculated as 1,463.08 million GJ due to additional energy requirement to meet SDGs. When benchmarking is considered with Targets 7.3 and 8.1, total energy demand is calculated as 1,618.87 million GJ by 2030. In this study, if there is no target for a specific indicator in Chile, additional energy is not considered. However, Target 2.4 and Target 12.5 may save energy or Target 11.2 may require more energy by 2030, which means that SDGs scenario could result in more or less energy than BAU by 2030 (Chapter 4).

- Due to its significant emission reduction target, the new NDC scenario has at least 38.5% reduction in energy demand when it is compared to reference scenario by 2030. Current policy and current policy+decarbonization scenarios had the same demand value near 980 million GJ. SDG scenario energy demand resulted higher than current policy scenario. NDC scenario has 20% of total energy demand reduction when the current policy has 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 NDC scenario (Chapter 5).

- 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 52.9% emission reduction when they are compared to 2016 value, that means they are also meeting the 45% emission reduction target by 2030 (Chapter 5).

- Although the energy transformation sector contributes to emissions significantly and policies have mostly been implemented to reduce emissions in the transformation sector, demand sector has a major contribution to the emissions in Chile when it is compared to transformation sector. The results showed that even though emissions from transformation sector demonstrate a significant reduction by 2030 in different scenarios, the decrease in demand side is not clearly noticed. Therefore, Chile also requires appropriate energy efficiency and renewable energy policies to be implemented for demand sides of transport, mining and other industries to reduce emissions at demand-side as it has decarbonization plan for transformation side. Reference scenario has the highest demand-side emission production, which is followed by NDC scenario when new NDC has the lowest value near 40 million metric tons of CO_2 emissions (Chapter 5).

- When the main sectors in demand are evaluated, the transport has the largest contribution to emissions and it is followed by industry, mining, public and commercial, and residential sector, respectively. When fuel contribution to emission is considered, diesel has the main contribution to the emissions, followed by gasoline, natural gas, LPG, jet kerosene, and oil. Diesel, jet kerosene and gasoline fuels usages in the transport sector have a significant contribution to emission. Diesel usage of the mining sector and major consumption of oil, diesel, natural gas, LPG and coal in industry sector also contribute to emissions directly (Chapter 5).

- NDC, new NDC, current policy, current policy+decarbonization and SDG scenarios showed essential emission reduction in 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 decarbonization scenario by 2030 (Chapter 5).

- 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 (Chapter 5).

- 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 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 (Chapter 5).

- It demonstrates 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 less emissions and more diversification in terms of energy production (Chapter 5).

1.5.3. Contributions

The major contributions of this dissertation are listed as follows. Note that the detailed contributions are explained in each chapter which includes the specific contributions of published and submitted journal articles.

- It provides a comprehensive review about the Chilean energy sector and policy development and helps understanding the energy sector situation in Chile
- It evaluates the current policy of Chile to understand renewable energy promotion in the latest year.
- It analyses the energy requirement of energy-related SDGs if Chile plans to meet these targets by 2030.
- It generates scenarios by considering the latest development in the energy sector and national and international promises of Chile in terms of energy and environment.
- It develops an energy model for the Chilean energy sector and evaluates several scenarios which have not studied in the literature so far.
- It compares developed scenarios to comprehend the best combination of policies towards de-carbonization and combating climate change.

1.5.4. Perspectives of future work

There are some interesting research areas as future studies in energy modelling, and they are listed as follows:

- Analyzing different energy policies and implementing them to Chilean energy model and realizing sensitivity analysis for determined scenarios
- Developing a detailed energy model for Chile including each region (SEN, SEA, SEM)

- Adding more futuristic technologies to the model to see their impact on the energy system in Chile.

1.5.5. Study limitations

This study has some limitation due to the nature of the research methods applied, due to the time and resource constraints, and finally due to the unavailable information.

- The study focuses on secondary data and literature reviews. Sources were identified via databases including Science Direct and Research Gate and open access search engines including Google and Google Scholar. As many international organization reports were part of the research, open access searches often returned results of more significant interest and relevance. Most sources were international organization reports, Chilean Government-related documents (Chapter 2, 3, 4, 5).

- All the analyses in Chapter 3 are shaped by the conditions of the country studied, the assessment criteria, and their importance for the country´s energy system. It may vary significantly from one country to another. Moreover, the methodology employed in this section can bring very different results for other countries due to having a certain degree of subjectivity in the experts' views and various potential limitations in the application of the method.

- The analyses in Chapter 4 are formed based on the conditions of the country studied, considered SDG assessment indicators, and energy requirement calculations based on literature review. In some indicator assessment, data were available for only a few years and the growth rate is calculated based on existing data sets. Also, if there is no target for a specific indicator in Chile, surplus energy is not considered. However, Target 2.4 and

Target 12.5 may save energy, in contrary, Target 11.2 may require extra energy in 2030. Also, the study only predicts energy demand.

- This modelling approach in chapter 5 is potentially limiting because it provides results for all Chilean energy sector not regional analysis for SEN, SEA or SEM. Also, this study does not consider sub-sectors of energy sectors in Chile due to time constraints and not having publicly available complete data sets.

- Another limitation is weather impacts on electricity generation. In this study (Chapter 5), LEAP could not consider weather impacts on renewable energy power plants such as hydroelectric, solar and wind. LEAP does not include any optimization capabilities and it does not have national data sets. The technology and emissions data in LEAP´s database is also quite limited in scope.

1.5.6. Summary of the chapter

In this section, the context, objectives, hypothesis, methodology, contents, main results, contributions, perspectives of future work and study limitations are presented. in the following section, the first step of the methodological approach which is also the first publication of this dissertation is explained in detail.

2. REVIEW AND ASSESSMENT OF ENERGY POLICY DEVELOPMENTS IN CHILE

In recent years, the Chilean energy sector has gone through a significant transformation. Chile ratified the Paris Agreement in 2017 and committed to develop policies to face climate change and to transition to a more sustainable energy system. Promoting renewable energy and energy efficiency became an essential strategy for Chile to reduce emissions and reach its energy and environmental goals, which are addressed in various governmental studies. Further, Chile became successful in promoting renewable electricity production without feed-in tariffs. The current national goal is for at least 70% of the electricity in Chile to be generated from renewable energy sources by 2050. Additionally, energy efficiency is to be implemented in several sectors. This paper provides a broad overview of the energy sector and review of the Chilean energy policy development and environmental targets with emphasis on recent years. Finally, it also proposes an assessment about existing and required energy policy instruments for Chilean energy sectors by considering the promotion of renewable energy and energy efficiency and analyses the associated potential challenges. This work can provide insights to decision makers to develop long-term sustainable energy plans for Chile to reach its energy and environmental goals.

2.1. Introduction

According to the BP Review of World Energy, approximately 85% of global energy demand is met by fossil fuels including oil, coal, and gas (British Petroleum, 2017). High demand growth, uncertain fuel price, and the rising concern about climate change force countries to have long-term, cost-effective, secure, and sustainable energy policies and long-term planning. Thus, many industrialized and developing countries have started to change their future energy plans towards de-carbonization.

One hundred and seventy-eight countries ratified the Paris Agreement to share the responsibility for the consequences of climate change, and they have been working on various solutions towards a sustainable future ("Paris Agreement - Status of Ratification," n.d.). In August 2010, Chile officially made a voluntary commitment to the United Nations that states, "Chile will take mitigation actions in order to achieve a deviation of 20% below its growing trajectory of business-as-usual emissions in 2020, projected from the year 2007" (Gobierno de Chile, 2013). In February 2017, Chile ratified the Paris Agreement and committed to developing policies on climate change and to achieve sustainable development objectives. In the scope of 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 (The Committee of Ministers for Sustainability and Climate Change, 2015). In addition to signing international agreements, Chile also set targets at the national level. According to the Law of Electrical Services, modified by Law Nº 20.936, every five years the Chilean Ministry of Energy will have to develop a long-term energy plan for different energy scenarios that include expansion of generation and energy demand, in a horizon of at least thirty years (Ministerio de Energía, 2017).

Additionally, Chile has significant renewable energy potential, which can contribute to the sustainability of future energy plans. The north of Chile has the best worldwide solar energy potential for energy generation, on account of dryness and clear sky (Escobar et al., 2015, 2014). Also, industry in the north of Chile is based on highly energy-intensive mining activities (Del Sol and Sauma, 2013).

This paper presents a comprehensive overview of the energy sector and review of energy policy development in Chile with an emphasis in the last eight years. The objective of the study is to evaluate the current energy policy of Chile to reach future energy targets by assessing policy instruments and studying existing challenges. The paper makes four contributions to the literature: i) It provides a broad overview of the Chilean energy sector by considering energy demand, generation mix, renewable energy potential, and the economic context. ii) It addresses the question of how energy policies in the last decade have been developed in Chile. iii) It summarizes the environmental commitments and main long-term energy targets of Chile and iv) it proposes an assessment about existing and required energy policy instruments for Chile by considering the promotion of renewable energy and energy efficiency to reach future energy goals and studies the various associated challenges.

The paper is organized as follows: Section 2 presents the methodological approach of the paper including the review and assessment processes. Section 3 includes an overview of the energy sector in Chile by considering energy access and sectors, characterization of energy demand and supply, renewable energy potential and generation, and the economic context. Section 4 describes energy policy development in Chile and actions taken by the government since 2011. Section 5 reviews the nationally determined contributions and principal energy targets of Chile. Section 6 presents a thorough assessment and discussion of energy policy instruments in terms of deployment of renewable energy and energy efficiency for Chile, as well as several challenges for the future of the Chilean energy sector. Finally, Section 7 concludes the paper and discusses future works.

2.2. Methodology

This research mainly has a two-part methodology including literature review and assessment. The cross-functional flowchart of the methodology is presented in Figure 2-1. For the overview and review sections, a systematic review of the literature was realized by utilizing relevant keywords (both in Spanish and English languages) in two scientific search engines (Science Direct and Google Scholar), Chilean governmental and non-governmental websites and energy-related international agencies. Also, in the section of current energy policy review, the years between 2011 and 2018 were chosen and reviewed due to significant developments in energy policy in Chile along that time. Moreover, nationally determined contribution and principle energy targets of Chile were revised and summarized to understand the future energy policy.

From all analysis of these reviews, it is understood that in parallel to the world, renewable energy promotion and energy efficiency will help Chile to reach its national and international targets. Therefore, the assessment in this paper seeks to clarify "what are" the current energy policy instruments related to renewable energy and energy efficiency in Chile by comparing the situation with respect to the rest of the world and also it seeks to identify "what should be considered in the future" by taking into account Chilean mining, industry, residential, transportation, public and commercial sectors. This analysis was realized in order to understand the contribution of current and required renewable energy and energy efficiency policy instruments to the future energy targets. Finally, after the assessment process, potential future energy policy challenges were determined to show and emphasize how future policies should be directed for Chile by decision-makers in the last part of the discussion section.

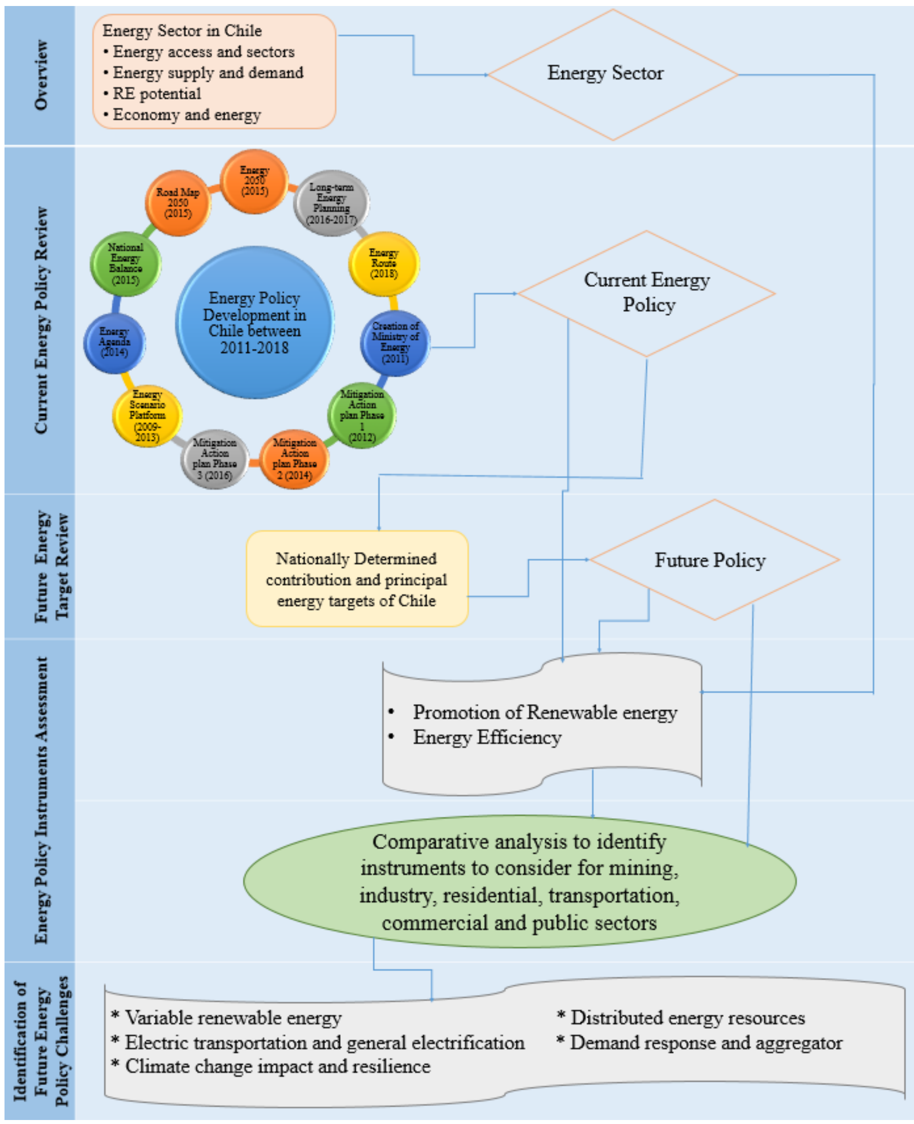


Figure 2- 1:Cross-functional flowchart of the methodology

2.3. Overview of the energy sector in Chile

2.3.1. Energy access and sectors

Chile has a unique geography due to its long and narrow shape. It is divided into fifteen regions from north to south. Until the end of 2017, Chile had four main electricity grids: the Northern Interconnected System (SING), the Central Interconnected System (SIC), the Aysen System (SEA), and the Magallanes System (SEM). Between these four grids, SIC and SING have the major capacity share with 75.8% (17081 MW) and 23.5% (5288 MW), respectively (CNE, 2017). In 2018, SING and SIC were combined, and the newly combined grid is now called the National Electricity System (Sistema Electrico Nacional-SEN). SEN encompasses thirteen regions and controls 99% of the total electricity supply of Chile, as shown in Figure 2-2 (CNE, 2018a).

In the northern regions, oil and natural gas are the main sources, while biomass (mostly firewood) has an important share in the southern part of the country. The energy supply has diversified in recent years with the inclusion of renewable energy, and the primary energy supply of Chile consists mainly of oil, coal, natural gas, biomass, hydro, solar, and wind sources. These sources are consumed in five main sectors: industry, mining, commercial and public, residential, and transport. Industry and transport constitute the biggest shares in the total consumption of energy, and mining activities, which take place in the northern regions of Chile (Ministerio de Energía, 2015a; Ministerio de Energía División de Prospectiva y Política, 2018), are also heavily energy intensive.

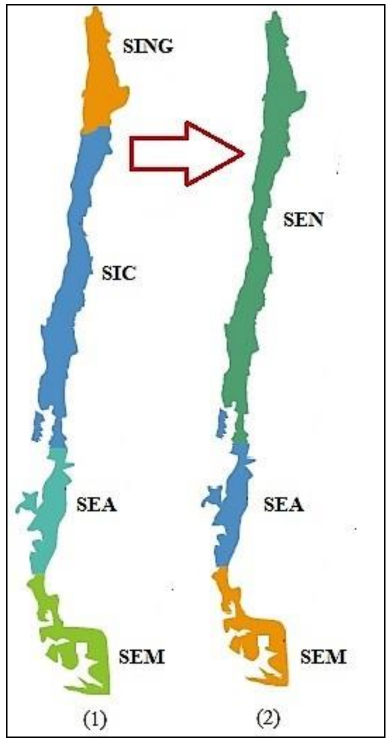


Figure 2- 2:National electricity grid in Chile (1); until December 2017 (2); after connecting SING and SIC as SEN in 2018.

(Figure constructed based on references (CNE, 2018a, 2017).)

2.3.2. Characterization of energy supply and demand

Chile mainly depends on imports for its domestic energy supply; the proportion was approximately 65% in 2016. The total primary energy supply (TPES) reached approximately 32 million tons of oil equivalent (Mtoe) in 2016, as shown in Figure 2-3.

Oil is the principal energy source, followed by biomass (mainly firewood), coal, natural gas, and hydro, respectively, as presented in Figure 2-4. The fossil fuel share of TPES is roughly 68%, which includes oil (29%), coal (24%), and natural gas (15%). Moreover, renewable energy has an essential contribution to TPES (32%); this source included biofuels and waste (25%), hydropower (6%), and wind and solar energy (1%) in 2016 (Ministerio de Energía División de Prospectiva y Política, 2018).

The total energy consumption corresponds to the energy destined for the consuming sectors of the national economy, both for energy and non-energy use. This total energy consumption in 2016 was 28.5 Mtoe, while it was 27.7 Mtoe in 2015. As illustrated in Figure 2-5, oil and electricity constitute a significant share of total consumption, and transportation and industry also constituted major shares of total energy consumption among other sectors in 2016.

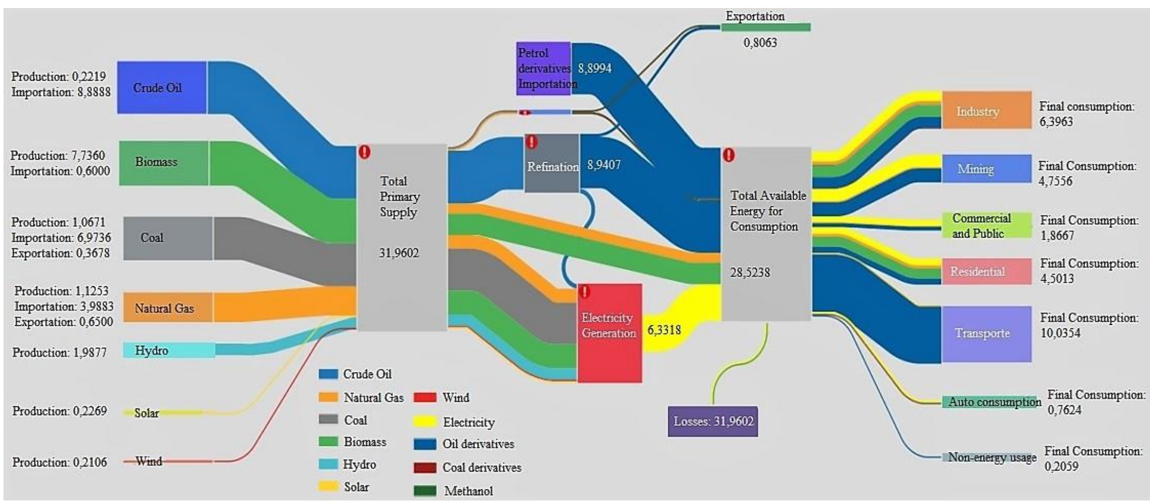


Figure 2- 3:The national energy balance of Chile in 2016 (all units in Mtoe).

(Figure translated into English for this paper based on reference (Ministerio de Energía División de Prospectiva y Política, 2018).)

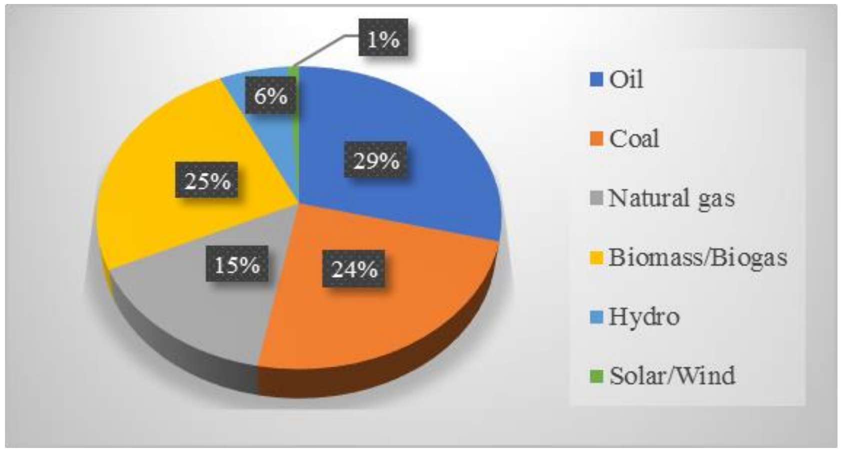


Figure 2- 4:Primary energy matrix in 2016 (Figure constructed based on reference (Ministerio de Energía División de Prospectiva y Política, 2018).)

As mentioned above, only 35% of Chile’s domestic energy needs are met by self-sufficiency; the rest are dependent on imported resources. Almost 98% of the necessary oil, 77% of natural gas, and 80% of coal were imported in 2016. Although natural gas and coal importation shares have fluctuated significantly depending on suppliers, oil has remained almost the same since 1990 (IEA, 2018; Ministerio de Energía División de Prospectiva y Política, 2018).

In 2016, the consumption of electrical energy, from both the power plants connected to the different interconnected systems and from the self-producing companies, varied by 3.9% with respect to 2015 electricity consumption (6.0468 Mtoe) and reached 6.2851 Mtoe. In Figure 2-6, total electricity consumption by sector is compared for 2015 and 2016. These show a similar tendency, and by 2016, electricity was consumed mainly by the mining sector (34%), industry (27%), the residential sector (17%), and the commercial and public sector (16%) (Ministerio de Energía División de Prospectiva y Política, 2018).

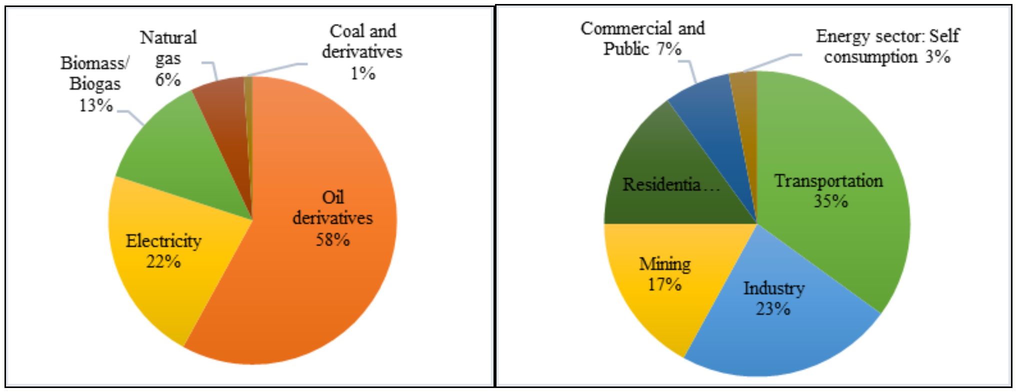


Figure 2- 5:Total energy consumption by sources (left) and sectors (right) in 2016. (Figure constructed based on reference (Ministerio de Energía División de Prospectiva y Política, 2018).)

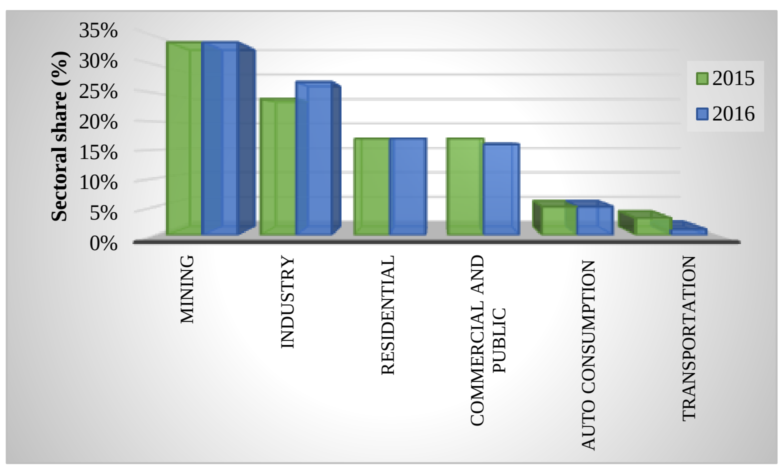


Figure 2- 6:Total electricity consumption by sector, 2015 and 2016. (Figure constructed based on reference (Ministerio de Energía División de Prospectiva y Política, 2018).)

2.3.3. Renewable energy potential and generation

Chile has remarkable potential for renewable energy. The country's northern region has one of the best worldwide solar energy potentials to generate electricity due to its dryness and clear sky (Escobar et al., 2015, 2014). In the north of the country, there are heavily energy-intensive mining activities, which consume 99% of the electricity generation in the region (Del Sol and Sauma, 2013). 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 (IEA, 2018; Santana et al., 2014).

In addition to these, it was estimated that Chile has a potential of 164 GW from the ocean due to its long Pacific coast, 16 GW from geothermal sources because of containing 10% of the most active volcanoes in the world, and 1.4 GW from biomass sources (Woodhouse and Meisen, 2011). Figure 2-7 shows the share of sources for total energy sources between the years 1973 and 2016. From this figure, it can be observed that the shares of hydropower and biomass have been very constant throughout the years 1973–2016. Additionally, despite the huge solar and wind potential, the contribution of these sources to the national energy balance appeared after 2010. In 2016, renewable energy shares, including biomass, hydro, wind, and solar, reached 34% of TPES. Besides transferring solar electricity from the north to the centre of Chile, researchers are investigating the possibility of solar electricity production and transmission to neighbouring countries such as Argentina and Bolivia (Fthenakis et al., 2014).

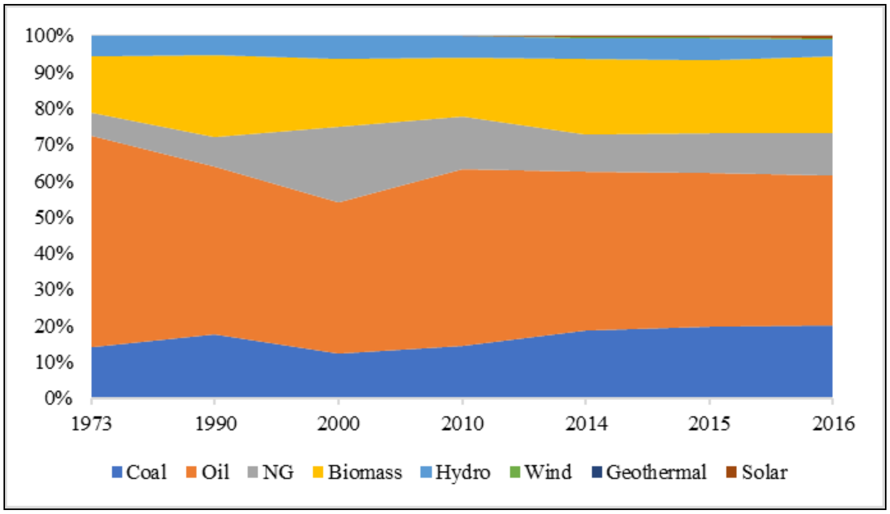


Figure 2- 7:The share of sources in TPES, 1973–2016 (Mtoe).

(Figure constructed from data in (IEA, 2018).)

The net installed capacity based on renewable energy technologies, including solar, wind, biomass, geothermal, and mini-hydro (hydro less than 20 MW capacity) (Ministerio de Economía, 2013) totalled 4110 MW as of December 2017, including 3443 MW in the SIC, 637 MW in SING, 26 MW in the electric system of Aysen, and 3 MW in Magallanes. In Figure 2-8, the total installed capacity of wind and solar energy sources in Chile between the years 2011 and 2017 is shown. It can be observed that solar and wind energy have a significant contribution to the renewable energy matrix in the most recent years (Grágeda et al., 2016; Zurita et al., 2018). Although wind energy projects were started in early 2011, solar energy caught the wind at the end of December 2016, and solar energy surpassed wind energy in Chile.

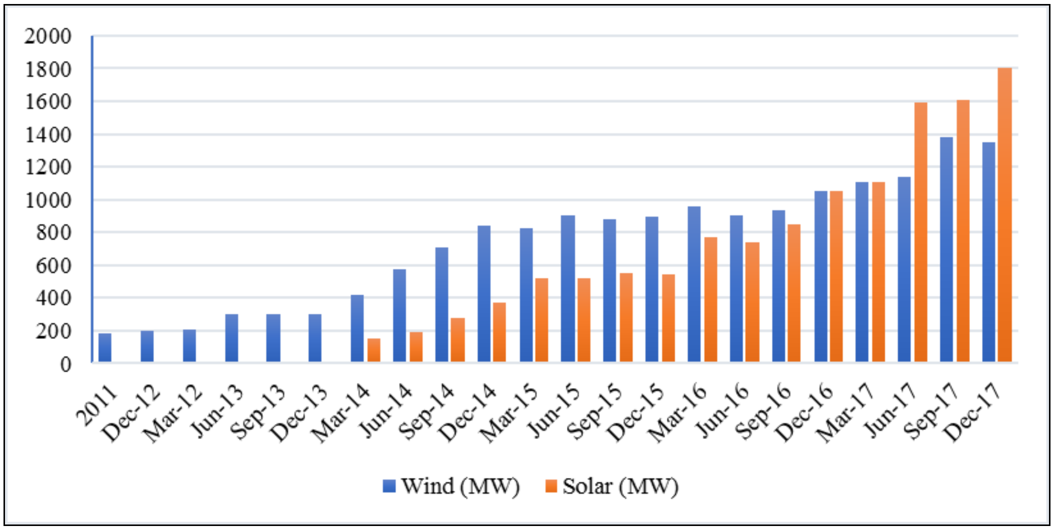


Figure 2- 8:The total installed capacity of wind and solar energy in Chile, 2011–2017. (Figure constructed from data in reference (CNE, n.d.).)

The installed renewable energy capacity corresponds to 18% of the total electrical generation capacity in the national electricity systems, in which mini-hydro has 2%, biomass has 2%, wind has 6%, and solar has 8%. Besides installed capacity, renewable energy generation reached 1146 GWh while energy generation was 5530 GWh from conventional energy sources, as shown in Figure 2-9. Solar PV, wind, and biomass have had a significant contribution to generation in the most recent years (CNE, 2018b).

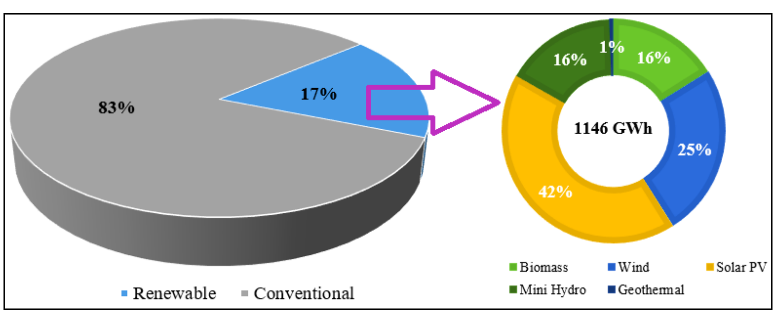


Figure 2- 9:Renewable and conventional energy generation by technology, until December 2017. (Figure constructed from data in (CNE, 2018b).)

2.3.4. Economy and energy context

The current population of Chile is approximately 18 million. Access to electricity for the urban and rural population has now reached 100% while it was only 92% in 1990 (The World Bank, 2018). In 2017, the country's GDP was 23,476 USD/capita, which was 115% higher than that in 1996 (IEA, 2018; OECD, 2018a), and the unemployment rate was 6.7%, which is more than the average of OECD countries (OECD, 2018b). Chile's copper resources are roughly 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. Thus, fluctuations in the global copper market affect Chile's national economy considerably. Although copper prices dropped dramatically from 2012 to 2016, the contribution of copper mining to the economy is still high, constituting 7.3% of GDP in 2016 (IEA, 2018; OECD, 2018c).

Due to Argentina's curtailing of natural gas exports to Chile, electricity prices for both households and industry reached the highest prices in 2008. After Chile spread energy sources out, especially by increasing electricity generation from coal, electricity prices started to drop. In the last years, prices have also fluctuated again due to changes in tariffs and tender results after the gas crisis. In 2016, electricity prices were approximately 120 USD/MWh and 170 USD/MWh for industry and household sectors, respectively (IEA, 2018).

2.4. Energy policy development in Chile between 2011 and 2018

The Ministry of Energy was created with law No. 20.402 in February 2010, and it obtained autonomy by being separated from the Ministry of Mining (Biblioteca del Congreso Nacional de Chile, 2012a; Congreso Nacional de Chile, 2009). Activities related to long-term energy planning in Chile have gained momentum and accelerated after the establishment of the energy ministry. Along with other worldwide developments related to climate change, Chile has begun to take decisive steps. Each of these developments is described in the remainder of this section.

2.4.1. The mitigation action plans and scenarios: MAPS-Chile project

The MAPS-Chile project originated following the example of a project carried out in South Africa. This South Africa project was the original MAPS project and motivated also other projects in countries including Brazil, Colombia, and Peru (Gobierno de Chile, 2014, 2013).

MAPS-Chile was a government project that developed projections and mitigation action plans to reduce greenhouse gas emissions in Chile (Gobierno de Chile, 2013, 2012; Ministerio del Medio Ambiente (Mitigation Action Plans and Scenarios), 2011). The project was started in 2012 and managed by an Inter-Ministerial Committee. It was carried out in three phases. During Phase 1, the projection of the baseline scenario for 2007–2030, or the *Growth without restrictions* and *Required by science* scenario, was carried out. In Phase 2, in development until the end of 2013, the baseline scenario for 2012–2030 and the different mitigation scenarios were projected. Finally, in Phase 3, all results were combined and interpreted for mitigation action plans (Gobierno de Chile, 2013). The growth without restrictions scenario does not consider any emission reduction actions and the energy policies continue as they are. The baseline scenario for 2012–2030 takes into the account year 2012 as the base year and includes several mitigation actions. The scenario Required by Science (RBS) allows Chile to meet the global goal of stabilization of global emissions to limit the increase in the average temperature of the terrestrial surface to less than 2°C above pre-industrial levels, in order to avoid the most dangerous effects of climate change (Gobierno de Chile, 2013, 2012). In the following sections, three phases of MAPS are explained and summarized in detail.

2.4.1.1. MAPS: Phase 1

In the first phase of the project, five different GHG emissions scenarios were developed for 2007–2030. In order to generate scenarios, key assumptions were determined. Besides the reference scenario, the projection of the GDP growth rate for the years 2007–2030 was determined by four scenarios:

- GDP pessimistic scenario: 3% growth rate
- GDP medium-low scenario: 4% growth rate
- GDP medium-high scenario: 5% growth rate
- GDP optimistic scenario: 6% growth rate

Figure 2-10 shows GHG emissions for five different scenarios between 2007 and 2030. GHG emission values for 2030 were obtained as follows: 214.8 MM ton CO_2eq for GDP reference scenario, 175.4 MM ton CO_2eq for GDP pessimistic, 223.0 MM ton CO_2eq for GDP medium-low, 283.7 MM ton CO_2eq for GDP medium-high, and 356.9 MM ton CO_2eq for GDP optimistic scenario (Gobierno de Chile, 2013).

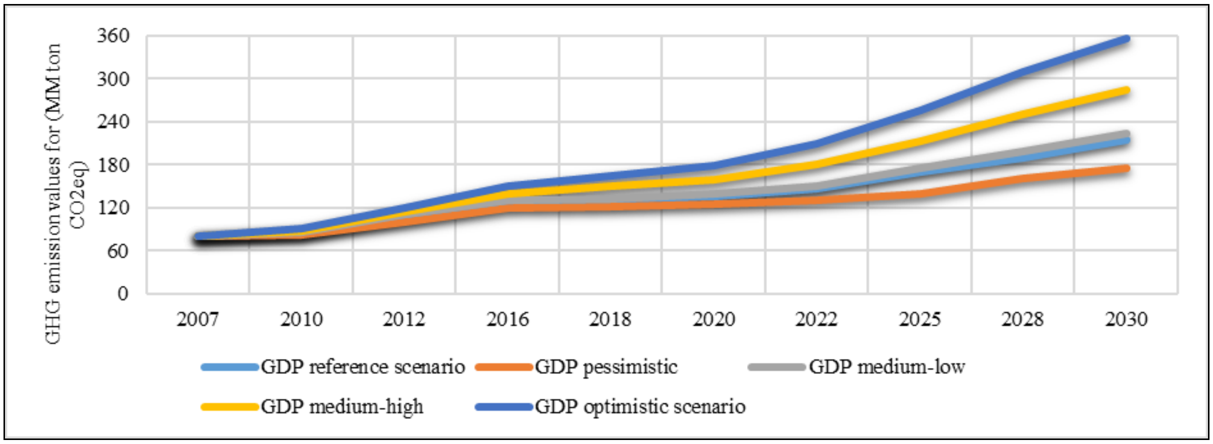


Figure 2- 10:GHG emissions for five different scenarios, 2007–2030, from the MAPS-Chile Phase 1 (Gobierno de Chile, 2013). (Figure constructed based on reference (Gobierno de Chile, 2013))

2.4.1.2. MAPS: Phase 2

In the second phase of the project, 2013 was taken as the base year, and the work was organized in a similar way to Phase 1. In this study, baseline scenarios, in which no mitigation was considered, were generated for the years between 2013 and 2030 and each sector's participation in total emissions of the baseline scenario were illustrated in the report. It was obtained that the generation/transport of electricity, transport, and industry/mining sectors make major contributions to total emissions.

After calculating the baseline 2013 scenario, the mitigation measures with the highest reduction potentials were presented for the 2013–2030 period. More than 96 mitigation measures for seven sectors were analysed; however, it was observed that 29 of them had more potential to contribute the highest reductions. The measures with the greatest abatement potentials for the 2013–2030 period were obtained for the generation/transport of electricity and transport sectors. To see the impact of measures on emission reductions, selected measures were combined and added to the baseline 2013 GDP medium scenario. Thus, more scenarios were developed, as follows (Gobierno de Chile, 2014):

- Energy efficiency (EE) scenario: Combination of mitigation measures related to energy efficiency.
- Carbon tax scenario: Considering the set of measures in which carbon taxes are applied.
- Non-conventional renewable energies (NCRE) scenario: Combination of all measures that include the incorporation of non-conventional renewable energies, among them solar, geothermal, wind, biomass, and small hydro.
- Renewable energies (RE) scenario: Combination of all the actions that include renewable energy from the NCRE scenario, plus large hydroelectric plants. This scenario considers, for example, the implementation of the HidroAysén project from the year 2021.
- 80/20 Scenario: Referring to a scenario that combines a reduced set of measures that adds a high mitigation potential.

In addition to these five special scenarios with mitigation measures determined, three more basic scenarios were considered in the analysis, as follows:

- Base scenario*:* considering 12.3% emissions reduction by 2030.
- Medium scenario*:* considering 29% emissions reduction by 2030.
- High scenario*:* considering 32.7% emissions reduction by 2030.

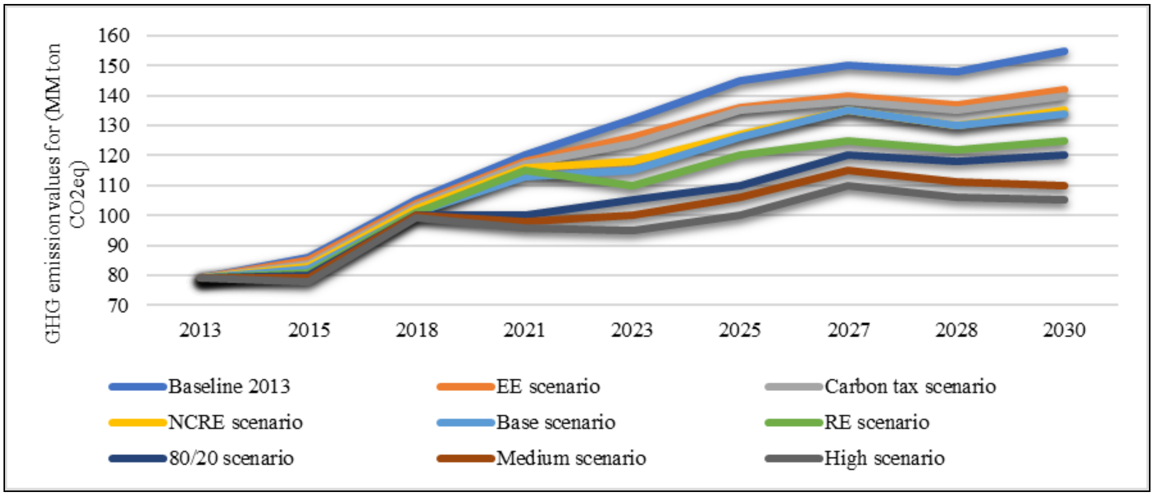


Figure 2- 11:Emission values of the year 2030 for the mitigation scenarios studied from the MAPS-Chile Phase 2 (Figure constructed based on reference (Gobierno de Chile, 2014))

In conclusion, nine different scenarios are compared in Figure 2-11. The emissions trajectory for these mitigation scenarios can be seen for the 2013–2030 period. The renewable energy, 80/20, medium, and high scenarios showed better results for emissions mitigation in 2030, while the energy efficiency, carbon tax, NCRE, and base scenarios produced fewer contributions to emissions reduction. Thus, the best mitigation measures were defined and their impacts were studied in the second phase of the MAPS-Chile project.

2.4.1.3. MAPS: Phase 3

The third phase of the MAPS-Chile project included several steps. First, refinements were realized for the work done during Phase 2. This included various revisions and iterations on the results already obtained from the previous stages. Additionally, an impact analysis was performed, which looked at the possible effects associated with the selected mitigation measures. Also, long-term mitigation analysis including a period until 2050 was considered in the third phase. Finally, public policy analysis was undertaken by considering the possibility of implementing the measures and the relationship between the mitigation measures and the relevant sectoral policies (Ministerio del Medio Ambiente y Gobierno de Chile, 2016).

2.4.2. Energy Scenarios platform (2009–2013)

In addition to governmental studies, energy-related actors have come together and performed some studies for the long-term period. Energy Scenarios (originally Escenarios Energéticos) was a multi-sectoral dialogue platform in which key actors representing the diverse visions of Chilean society participated. It began in 2009 with two strategic objectives: the construction and discussion of different scenarios for electric energy generation by 2030, and the generation of tools for the formulation of a public energy policy (Escenarios energeticos, 2018). The members of the platform met regularly and developed a work plan and methodology during 2009 and 2010 (Centro de Energia; Universidad Adolfo Ibanez; EECG Consultores, 2017).

Then, in 2011, four scenarios were proposed for electricity expansion planning for the central (SIC) and northern (SING) interconnected systems of Chile until 2030. First, two projections were realized by considering that no radical change would be incorporated into the composition of the electricity matrix: Market Criteria SIC and SING, respectively. Other scenarios are called Renewable SIC and SING scenarios and corresponded to a vision where renewable energy had a high contribution to the electricity matrix. In the case of the SIC, a high penetration of geothermal energy, and for the SING, a high participation of solar energy was taken into account. (Dufey et al., 2013). The capacity share based on sources for 2030 are illustrated for each scenario in Figure 2-12. As presented in the pie charts, the share of solar PV, wind and geothermal showed a significant increase in SIC while solar PV, solar CSP and natural gas play important role in the SING. Also, it is interesting to see that coal and diesel do not exist in the capacity share for 2030; high renewable penetration scenarios for SIC and SING.

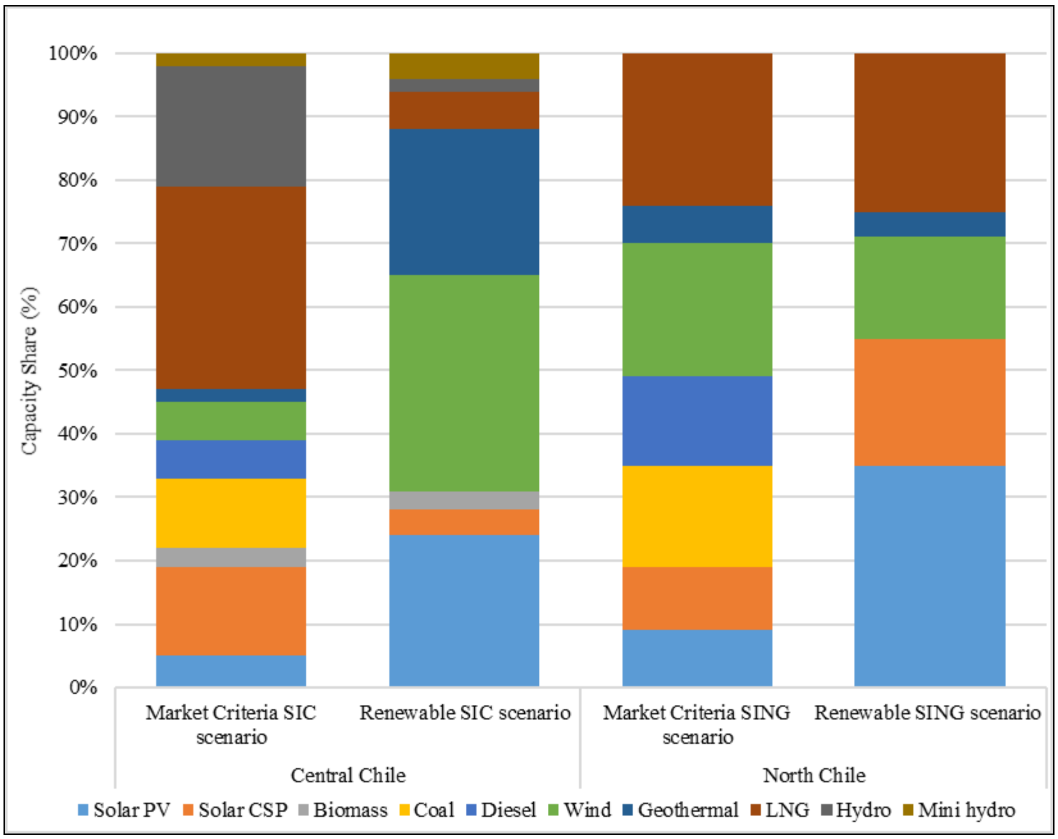


Figure 2- 12:The capacity share based on sources for 2030 in the study of the Energy Scenarios platform for the scenarios of Market Criteria and Renewable SIC and SING (Dufey et al., 2013) (Figure constructed based on reference (Dufey et al., 2013))

2.4.3. Energy agenda (2014)

In 2014, the Energy Ministry of Chile decided to develop an agenda that included national action plans to have reliable, sustainable, inclusive, and reasonably priced energy. This agenda was urgent because Chile imported 60% of its primary energy in 2014, which meant high dependency on foreign resources. Therefore, with the energy agenda, a new role for the Chilean government and the goals were defined for future energy policy (Ministerio de Energía, 2014). This agenda was an essential step in terms of defining new roles for government and energy-related actors and also because of stabilizing the long-term energy planning in Chile.

2.4.4. National Energy Balance (2015)

After defining new roles and goals for future energy planning, an energy balance study was conducted by the Ministry of Energy in 2015. The National Energy Balance study (Balance Nacional de Energía) was a useful tool that explained the reality of the country's energy sector in an integrated and comparative way for 2015. The report also illustrated the different energy flows from production to consumption, as well as the sectoral and regional energy balance. This study provided an essential example for future long-term energy plans. The NEB flowchart summarizes the transactions involved in the national energy chain, from acquisition or generation to transformations and final consumption (Ministerio de Energía, 2015a).

2.4.5. Road Map 2050 (2015)

The Road Map (Hoja de Ruta) was a preparatory study for Energy Agenda 2050. The advisory committee, a group of twenty-seven experts from various fields related to the energy sector, worked for a year on the development of a roadmap towards a sustainable and inclusive energy future for Chile. It contained the key items of the long-term energy policy as promised in Energy Agenda. Thus, it contained the fundamental inputs to prepare Energy Agenda 2050: Chilean's Energy Policy (Comité Consultivo de Energía 2050, 2015). As shown in Figure 2-13, five sectors and five cross-cutting issues were considered with this guideline. Then, the strategic axes of the roadmap were determined as shown in the figure (Comité Consultivo de Energía 2050, 2015).

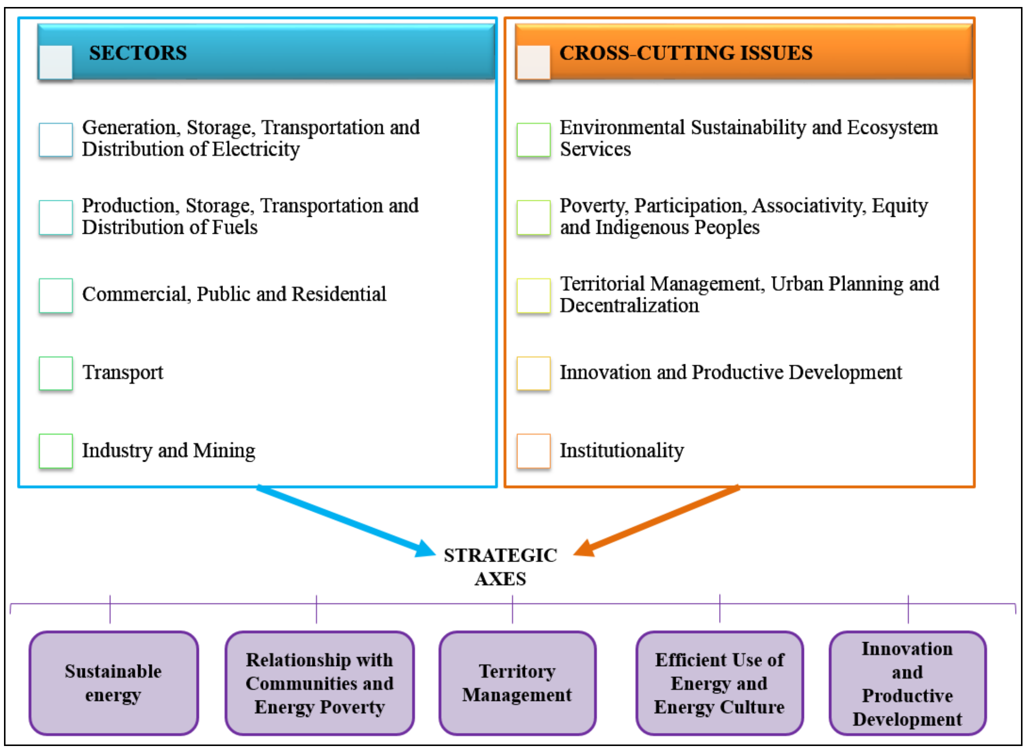
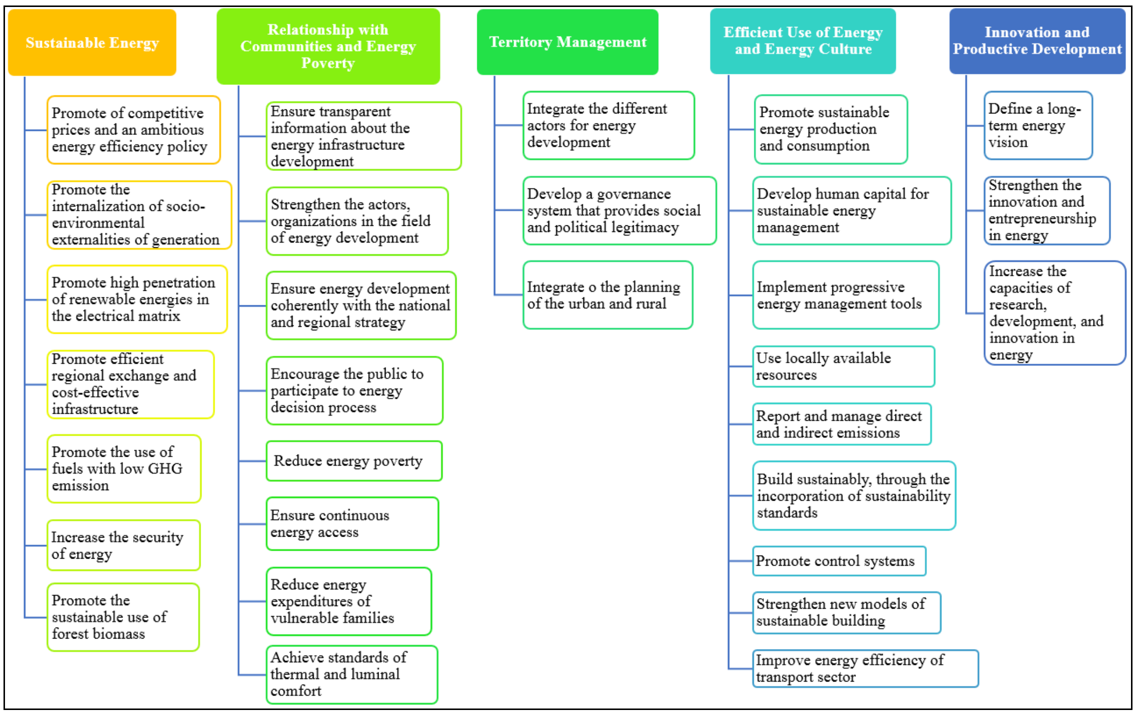


Figure 2- 13:Strategic axes of Roadmap 2050 study (Figure constructed based on reference (Comité Consultivo de Energía 2050, 2015)).

Table 2- 1:Summary of strategic guidelines in Roadmap 2050

(Table constructed based on information in reference (Comité Consultivo de Energía 2050, 2015)).



Based on these strategic pillars, detailed targets, actions, goals for 2035 and 2050, and actors were established in the Road Map. Table 2-1 lists the main strategic action decisions of the plan. Detailed actions and goals for each pillar can be found in the original document. The highest number of actions were decided for the efficient use of energy and energy culture, sustainable energy, and relationship with communities and energy poverty. However, all strategic axes of Roadmap 2050 included essential actions, such as promotion of renewable energy, with a minimum of 70% by 2050, reduction of energy poverty, improvement of energy efficiency for transport (Comité Consultivo de Energía 2050, 2015).

2.4.6. Energy 2050 (2015)

Five strategic axes and actions for the new Chilean energy policy were defined in the Road Map 2050. Then, all these decisions were combined, and Chile’s new energy policy was announced and published in 2015 as Energy 2050.

In that new report, Chile’s energy sector would have a reliable, inclusive, competitive, and sustainable vision by the year 2050. In order to realize the new vision, the policy was built on four main pillars as listed in Table 2-2: quality and security of supply, energy as a driver of development, environmentally friendly energy, and energy efficiency and energy education. As a first pillar, the quality and security of supply were considered due to having a reliable energy system. Secondly, the new energy policy was based on the vision of energy as a driving force for development. Thus, in order to have growth, Chile must have complete energy development including access equality, regional planning, and competitive prices (Ministerio de Energía, 2015b).

Table 2- 2:Actions for each pillar of Energy Policy 2050 (Table constructed based on information in reference (Ministerio de Energía, 2015b)).

Quality and Security of Supply

- Develop plans for managing risks in energy sector
- Promote a cost-effective infrastructure
- Increase the security of the supply
- Promote the exploration of Chile's hydrocarbon resources
- Promote the decentralization of energy
- Promote flexibility of the electricity system
- Ensure continuous access to the entire population

Environmentally Friendly Energy

- Promote renewable energy
- Promote sustainable hydroelectricity
- Promote fuels with low GHG emissions
- Promote the sustainable production of forest biomass
- Promote the reduction of GHG emissions
- Manage direct and indirect emissions

Energy as a Driving Force for Development

- Empower stakeholders, organizations, and communities in the area of energy development
- Promote local energy developments
- Ensure formal and pertinent public participation processes
- Reduce energy poverty
- Set standards of thermal and lighting comfort in the homes
- Integrate stakeholders, sectors for energy development.
- Integrate urban and rural
- Improve transport efficiency.
- Promote competitive prices
- Improve science, technology, and innovation in energy
- Reduce barriers to innovation and entrepreneurship

Energy Efficiency and Energy Education

- Form a robust market for energy service companies
- Progressively implement energy management tools
- Use local resources and explore potential energy savings
- Build energy efficiency standards
- Promote intelligent energy management
- Strengthen the market for efficient buildings
- Improve the energy efficiency of vehicles
- Promote more efficient transport
- Ensure clear and transparent information for citizens
- Design, implement, and monitor an energy education strategy
- Develop professional and technical human capital for the sustainable energy

The third pillar of the new policy was environmentally friendly energy, which meant that the development of the energy sector cannot be separated from local and global environmental impacts. Finally, energy efficiency and energy education were taken as the fourth pillar of the new policy by considering the implementation of improvements in energy efficiency (Ministerio de Energía, 2015b).

2.4.7. Long-term energy planning (2016–2017)

After the determination of energy policies and the main objectives for 2050, the government of Chile examined the different examples in the world to calculate the long-term energy plans quantitatively. Then, the methodology was developed for Chile to select robust energy scenarios in long-term energy planning (Centro de Energia; Universidad Adolfo Ibanez; EECG Consultores, 2017). Based on these changing factors, electricity expansion planning for each scenario was calculated, and the detailed results for generation and installed capacity for 2046 can be found in the original report. According to the scenarios developed in the study, a significant share of solar energy technologies (both concentrated solar power and photovoltaic) and wind energy were obtained for electricity capacity expansion and generation in 2046 (Ministerio de Energía, 2017).

Additionally, sectoral participation in energy consumption was studied for three different scenarios as summarized in Figure 2-14. Low, medium and high energy demand and energy sectors were considered. It can be inferred that while the share of the transport sector in energy consumption reduces significantly in 2046, the contribution of industry and mining sectors increase when they are compared to the year 2015. The shares of public and commercial sector do not show essential changes in 2046.

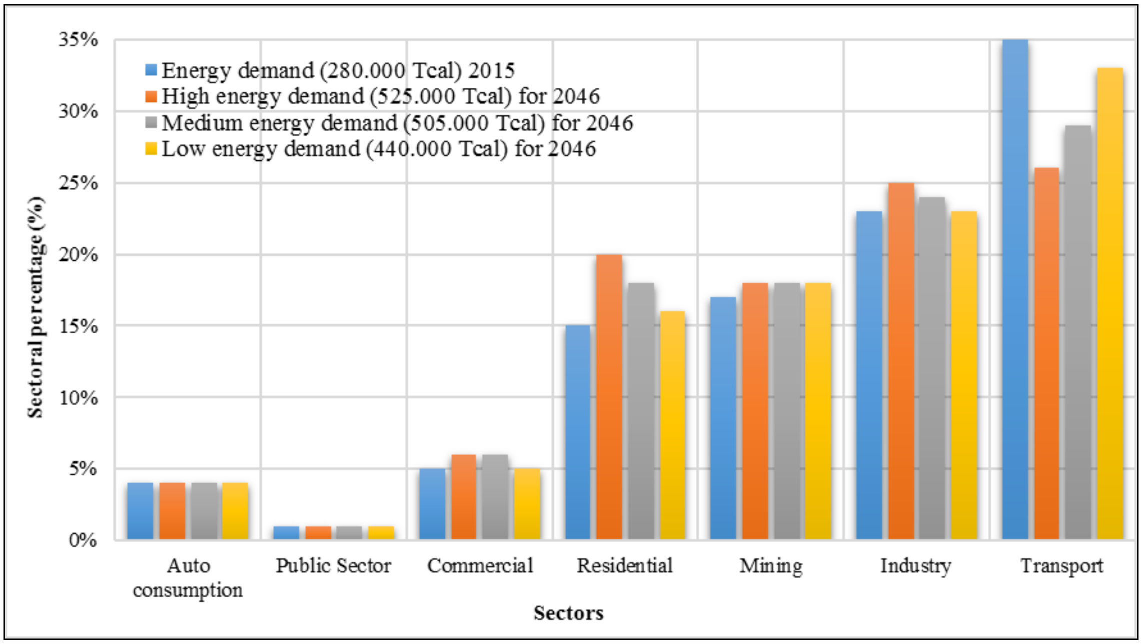


Figure 2- 14:Sectoral participation in energy consumption for developed scenarios (Figure constructed based on information in reference (Ministerio de Energía, 2017)))

2.4.8. Climate change adaptation plan (2017)

Throughout the process of assessing the development of a sustainable energy future for Chile, the Ministry of Energy conducted the preparation of a preliminary draft on a climate change adaptation plan in the energy sector of Chile with the support of the Ministry of the Environment. In this work, the impacts of climate change and adaptation measures were identified and prioritized by the contribution of national and international consultants, experts and the general public. First of all, the observed and projected climate trends in Chile were determined as follows: temperature, precipitation, external events, and the increase in sea level. After that, to assess the vulnerability of the Chilean energy sector due to climate change, a conceptual structure was developed based on the international examples by considering energy supply, energy transport (transmission and distribution), and demand. After determination of potentially affected subjects in the energy sector, action plans were developed for each impact. Finally, this work included actions to combat climate change, and also activities to promote renewable energy and energy efficiency to mitigate greenhouse gases (Ministerio del Medio Ambiente (Mitigation Action Plans and Scenarios), 2017).

2.4.9. Energy Route 2018-2022 (2018)

After the elections in 2017, there was a change of the status that the new government took over in March 2018 and a new study was published that revealed the energy approach of the new government. As a result of workshops and meetings held in every region of Chile with the participation of experts and the general public, the Energy Route 2018-2022 was published. The main axes of the new government's route towards sustainable energy were defined with this study as follows: energy modernization, energy with a social seal, energy development, efficient transportation, low energy emissions, energy efficiency, and energy education and training.

In the report, small-scale renewable energy promotion was explicitly mentioned by aiming four times more capacity expansion of small-scale (less than 300 kW) distributed renewable generation by 2022. Additionally, for the transport sector, it was targeted that the number of electric vehicles in the country will be increased at least ten times. As of the promotion of renewable energy, the new government also declared that regulatory framework for energy efficiency in the sectors of industry, mining, transport and buildings will be developed to have a sustainable energy utilization (Ministerio de Energía, 2018).

Besides the energy route which is complementary to the long-term policy Energy 2050, Energy Efficiency Law project was presented to the Senate by the Ministry of Energy in 2018. The proposed law aims 7% energy saving with respect to final consumption by 2035. Thus, this law will contribute with a share of 27% to the goals proposed in the greenhouse gas mitigation plan for the energy sector (Ministerío de Energía, 2018).

2.4.10. Energy Scenarios: Future of energy in Chile (2018)

Energy scenario platform carried out another study which is the continuation of the previous study and which describes the most recent trends in the energy sector of Chile. As shown in Figure 2-15, three “megatrends” and eleven cross-sectional trends were determined.

Moreover, depending on these three megatrends, related factors and specific trends were defined. Integration of renewable energies, electric mobility and energy efficiency are explicitly mentioned to consider for decarbonization and decontamination in the future energy matrix in Chile. Also, micro-grids, smart grids and energy storage are cited in the study as a future specific trend for decentralization and distributed energy, which are significant expected developments in the future (Escenarios energeticos, 2018).

In order to conclude this section, in parallel with worldwide actions for climate change adaptation, Chile has undertaken several energy studies from 2011 to 2018. These significant works were summarized in this section. After this review of the important historical background of energy policy development, Chile´s energy and environmental goals in the upcoming years will be discussed in the following section.

Megatrends		
De-carbonization and decontamination	De-centralization and distributed energy	Digital transformation
Factors of change		
○ De-carbonization policies ○ Carbon price integration ○ Impact of climate change ○ Costs of energy sources ○ Decontamination plans ○ The regulatory framework for emissions	○ De-centralization policies and strategies ○ Regional energy policies and plans ○ Local energy strategies ○ Renewable energy regulatory framework	○ Digitization strategies ○ The regulatory framework of digitalization ○ Strategies for smart cities
Specific trends		
▪ Integration of renewable energies ▪ Solar energy ▪ Demand for clean energy in the private sector ▪ Role of flexibility and system management ▪ Regional integration and decarbonization ▪ Non-motorized transport ▪ Public transport ▪ Electric mobility ▪ Other technologies for low emission vehicles ▪ Energy efficiency in electricity ▪ Thermal energy efficiency	▪ Small generation units ▪ Small residential generators ▪ Micro-grids and smart grids ▪ Storage ▪ Local associative investment ▪ Transmission ▪ District energy	▪ Networks and smart meters ▪ New business models ▪ Energetic geo information platforms ▪ Blockchain and peer to peer platforms ▪ Interactive and participatory platforms ▪ Autonomous vehicles ▪ Big data management analysis

Figure 2- 15:Aspects that shape the future of energy in Chile

(Figure constructed based on reference (Escenarios energeticos, 2018)

2.5. Nationally determined contributions and principal energy targets

In this section, the revised nationally determined contributions and principal energy targets of Chile for 2035 and 2050 were mentioned and listed.

Worldwide, the majority of countries determined their Intended Nationally Determined Contributions, which became Nationally Determined Contributions (NDCs) after ratifying the Paris Agreement (Griffiths, 2017). In 2015, Chile presented its intended national contribution to the United Nations Framework Convention on Climate Change. Chile's NDCs depended on five basic pillars: mitigation, adaptation, capacity building and strengthening, technology development and transfer, and financing. NDCs on mitigation were committed to two main targets: an unconditional target to reduce the GHG-emissions intensity of the economy by 30% below the 2007 level by 2030, and a conditional target of a 35%–45% reduction in GHG emissions intensity subject to international financial support.

In addition to GHG emissions, Chile committed to the sustainable development and recovery of 100,000 hectares of forest land, mainly native, which will account for greenhouse gas sequestrations and reductions of an annual equivalent of around 600,000 of CO_2 as of 2030 (The Committee of Ministers for Sustainability and Climate Change, 2015).

Moreover, in Energy Policy 2050 (Ministerio de Energía, 2015b), principal energy objectives were defined for the years 2035 and 2050, as illustrated in Table 2-3. For 2035, major targets were defined by considering Chile's interconnection with other countries, limits on electricity outages, energy access, renewable energy electricity generation targets, emission targets, energy efficiency, and regulations in transportation.

In addition to the main concerns for 2035, land use and GDP growth were taken into account in devising the principal energy goals for 2050. Between these targets, electricity generation from renewable energy sources and the implementation of energy efficiency measures by 100% of the large energy consumers are expected to have an important contribution to reaching energy and environmental objectives.

Table 2- 3:Principal energy goals for 2035 and 2050 from Energy 2050 (Table constructed based on information in reference (Ministerio de Energía, 2015b)).

2035	2050
Chile’s interconnection with the other South American countries	
Electricity outages less than 4 hours/year	Electricity outages less than 1 hours/year
100% quality access to energy services	100% quality access to energy services
Lowest average residential and industrial electricity prices	Lowest average residential and industrial electricity prices
At least 60% of the electricity generation from renewable energy	At least 70% of the electricity generation from renewable energy
By 2030, at least 30% GHG emissions reduction compared to 2007	International and national GHG emissions reduction targets
Efficient use of energy	100% of new buildings with OECD standards for efficient construction
Promote Energy efficiency for public transportation systems	100% energy efficient appliances and equipment
Regulate forest biomass utilization	Develop Energy culture for citizens

Finally, in addition to environmental and energy targets due to climate change concern, Chile should consider other issues among the seventeen sustainable development goals and take actions to improve its worldwide score by taking into account the most recent challenge of setting more stringent standards aimed at limiting global warming to 1.5 ºC (IPCC, 2018).

2.6. Assessment and Discussion

From the revision of energy policy development in Chile (Section 4 and 5), it is understood that the integration of renewable energy and energy efficiency are explicitly mentioned to consider for decarbonization and decontamination in the future energy matrix in Chile.

Therefore, in this section, current energy policy instruments related to renewable energy and energy efficiency in the world and in Chile were addressed and evaluated by using a comparative assessment process. This analysis was realized to understand how renewable energy is promoted in the world and how it is being achieved in Chile. Also, required policy instruments were briefly identified for each sector. After the assessment process, potential future energy policy challenges are determined and explained to guide decision makers to create sustainable future energy policies.

2.6.1. Assessment of energy policy instruments

Energy policy instruments are governments' actions to stimulate and try to achieve different potential energy policy objectives. These instruments must be specifically chosen for the country's unique situation by considering environmental effectiveness, cost-effectiveness, complexity, distributional issues, institutional feasibility and political issues, government costs, and the opportunity to leverage international funding. Also, it is not a simple process to understand the interactions among different individual energy policy instruments; thus it is challenging to select a proper combination of policy instruments (Benitez, 2012). In particular, when combining instruments, it is important to analyse whether the combination of several policy instruments has more added value than other combinations or single instruments (Löschel and Zew, 2012; Oikonomou et al., 2014).

In most of the studies for Chile reviewed in this paper, it is very clear that the contribution of renewable energy and energy efficiency to the low-carbon economy of 2050 has been emphasized strongly. Therefore, in this section, current and appropriate energy policy instruments for the different Chilean energy sectors are discussed by considering the important pillars of Energy Policy 2050.

2.6.1.1. The promotion of renewable energy

Promoting renewable energy is one of the key actions to fight against climate change worldwide. Political and scientific committees agree that renewable energy has to perform an essential role in the pathway to a low-carbon economy (Löschel and Zew, 2012). Besides developed countries like Germany, Spain, and the United States, developing countries such as India and China have recently started to significantly support renewable energy (Thapar et al., 2016). Depending on the country, some policy instruments are required in order to increase renewable energy share and make it competitive against conventional technologies. In different studies, various classifications can be found for energy policy instruments (Benitez, 2012; IRENA, 2012; Oikonomou and Jepma, 2008; Park, 2006; Perrels, 2001; Regulation Body of Knowledge, n.d.; Thapar et al., 2016; Warbroek, 2013). The key energy policy instruments used worldwide in support of the deployment of renewable power are these: fiscal incentives, public finance, and regulations (Benitez, 2012; Elizondo Azuela and Barroso, 2011; IRENA, 2012; Thapar et al., 2016).

FITs, tax incentives, and tradable green certificates are support mechanisms commonly used by governments to promote renewable energy (Abolhosseini and Heshmati, 2014; Thapar et al., 2016). FITs, quotas, tendering, and tax measures are especially being utilized by European countries to increase the share of electricity produced from renewable energy sources (Löschel and Zew, 2012; Ragwitz et al., 2006). However, it has been shown that although FITs are more effective (Warbroek, 2013), they can be relatively expensive when compared to quota mechanisms (Elizondo Azuela and Barroso, 2011). Further, renewable energy deployment has accelerated considerably in various Latin America countries such as Mexico, Chile, and Brazil (IRENA, 2015a).

In contrast to the EU countries, Chile is one of the countries that have been successful in the promotion of renewable electricity production without fiscal incentives or FITs. The development of renewable energy capacity in Chile without any incentives is remarkable. Chile currently has a renewable energy target, quota obligation, auctions, net metering, certificate system, and grid access, as well as some fiscal incentives for rural areas in electricity production (IRENA, 2015a, 2015b). In 2013, Chile set a target to produce 20% of its electricity from renewable energy sources by 2025 (IRENA, 2015b). After this short-term target, a new long-term target was set in Energy 2050 (Ministerio de Energía, 2015b) study: at least 70% of the electricity generated in Chile will come from renewable energy sources by 2050. Based on its targets, Chile has a quota obligation as the main policy instrument.

In the Chilean Renewable Energy Law signed in 2013 (Ministerio de Economía, 2013), renewable energy quotas were defined as 12% in 2020, 18% in 2024, and 20% in 2025 (excluding large hydro). Auctions for electricity production are another important support mechanism for Chile. They allow all types of renewable energy generators to have 10-year power purchase agreements with distribution companies. Also, Chile uses net metering, which permits consumers to produce their own electricity from renewable energy sources and inject extra generation into the grid. Additionally, the current law allows renewable energy generators under 9 MW to be exempt from grid access fees. Moreover, Chile provides technology-specific support and regulations especially for biomass, geothermal (exploration and exploitation of resources), concentrated solar power, solar roof application, and small hydro (IRENA, 2015b, 2015a).

Table 2- 4:Energy policy instruments used in the world and in Chile to promote renewable energy

<table>
<tr><th>Energy policy instruments used in the world to promote renewable energy</th><th>Energy policy instruments status quo in Chile</th><th>Instruments to consider for energy sectors</th></tr>
<tr><td>Fiscal incentives
(grants, energy production payments, rebates, tax credits, tax concessions/exemptions)</td><td rowspan="4">• Renewable energy target
• Quota obligation
• Auctions
• Net metering
• Certificate system
• Priority grid access
• Fiscal incentives for rural areas in electricity production
• Carbon tax
• Subsidies for disaster-affected regions
• Tax-exempt fiscal incentives for biodiesel and bioethanol
• Regulations for mixing bioethanol and biodiesel
• Direct support for electricity access in rural and indigenous regions and agriculture</td><td>Mining and Industry:
○ Priority or guaranteed access to networks
○ Priority dispatch
○ Tax credits
○ Production-based incentives
○ Soft loans</td></tr>
<tr><td>Public finance
(investments, guarantees, loans, public procurement)</td><td>Residential:
○ Grants
○ Tax exemptions
○ Loans
○ Green energy purchasing
○ Green labelling
○ Priority access to the grid</td></tr>
<tr><td rowspan="2">Regulations
(renewable portfolio standards/quota obligations or mandates, auctions, tendering, bidding, feed-in-tariffs (FITs), premium payment FITs, green energy purchasing, green labelling, net metering, priority or guaranteed access to networks, priority dispatch)</td><td>Commercial and Public:
○ Tax credits
○ Loans
○ Green labelling
○ Priority or guaranteed access to networks
○ Priority dispatch</td></tr>
<tr><td>Transportation
○ Tax credits/exemptions
○ Loans
○ Green labelling
○ Mandatory certification
○ Regulations</td></tr>
</table>

Furthermore, a carbon tax was passed in September 2014 with the tax reform law 20.780, which states that a yearly tax of 5 USD/tonneCO_2 will be applied to the emissions of power plants exceeding 50 MW capacity (except biomass) (IRENA, 2015a; The Committee of Ministers for Sustainability and Climate Change, 2015). The only direct support in the form of subsidies in Chile is given for solar heating in the reconstruction of disaster-affected regions such as Arica, Iquique, and Valparaíso (IRENA, 2015a, 2015b).

In the transport sector, Chile has tax-exempt fiscal incentives for biodiesel and bioethanol, and regulations for mixing bioethanol and biodiesel with gasoline and diesel at 2% and 5%, respectively. Finally, Chile provides some support for electricity access in rural and indigenous regions, PV production in countryside, and solar energy for agriculture (IRENA, 2015b).

It can be seen that there are several efforts in almost all sectors in Chile in terms of deployment of renewable energy. However, in order to reach the targets proposed, other instruments could also be considered by the government as presented in Table 2-4. For instance, mining activities, which take place in the north of Chile, are characterized by very significant energy consumption as compared to other sectors. Therefore, it is worthwhile to investigate specially designed policy instruments to exploit potential synergies between the mining and solar power industries. For example, tax credits and production-based incentives can be studied to lower the levelized cost of energy and reduce the governmental cost for concentrated solar power technologies in Chile (Simsek et al., 2018b). Also, priority or guaranteed access to networks, priority dispatch, tax credits and soft loans should be considered for mining and industry sectors. The residential, public and commercial sectors can be supported with incentives for rooftop photovoltaics to create more distributed self-producers. Finally, new mandatory and economic instruments could be studied for the transport sector to be prepared for the upcoming electric-transportation revolution.

2.6.1.2. Energy efficiency

Energy efficiency is another significant issue in aiming towards a sustainable energy future. Both industrialized and developing countries are trying to adopt energy efficiency in several energy sectors (Jedlicka et al., 2005; Löschel and Zew, 2012). Denmark is a good example of having since 1997 an obligatory building energy-efficiency label program. Additionally, countries such as China, Italy, and the United States have policy instruments for promoting energy-efficient programs in the building sector. The approach to energy efficiency promotion shows the changes between countries.

The literature features mostly building/residential energy efficiency studies due to a relatively high potential for energy savings from reduced inefficiency (Boza-Kiss et al., 2013; Bye et al., 2018; Filippini et al., 2014; Kern et al., 2017; Madlener and Stagl, 2005; Shen et al., 2016). For instance, Australia, Japan, and China have more mandatory instruments, while the EU has adjusted a large number of both economic instruments and mandatory instruments in order to promote energy efficiency in buildings. On the other hand, the United States has preferred voluntary instruments to increase energy efficiency activities. Depending on the country, the implementation of mandatory, economic, and voluntary instruments can encounter several barriers and complications.

To minimize the risks in practice, a combination of energy efficiency policy instruments should be considered by governments (Kern et al., 2017; Shen et al., 2016). Not only energy efficiency instruments but also energy efficiency and renewable energy promotion instruments can be combined to reach environmental and energy targets (Oikonomou et al., 2014). Also, the costs of investing in energy efficiency improvements must be studied for particular countries and their conditions (Bye et al., 2018). A study about building energy efficiency stated that product energy performance standards and their combination with product labels showed considerably better results regarding environmental and cost-effectiveness than any other instrument. Building codes have been the most utilized policy instruments, chosen by more than thirty countries (Boza-Kiss et al., 2013; Karlstrøm and Ryghaug, 2015). Moreover, for the EU residential sector, financial incentives and energy performance standards have shown significant effects in stimulating energy efficiency improvement, although informative measures such as labelling and educational campaigns have not been shown to have noteworthy results (Filippini et al., 2014).

In order to aim toward a sustainable energy future, energy efficiency has gained in importance for Chile. In 2009, the law (20.420) of the creation of Energy Ministry of Chile also included the decision to establish minimum energy performance standards (MEPS) and definition of the products that must have an energy efficiency label (Biblioteca del Congreso Nacional de Chile, 2012a). After that, in 2012, a decree about regulations to establish the procedure for setting MEPS and their application was launched (Biblioteca del Congreso Nacional de Chile, 2012b). Also, stimulation of energy efficiency in several sectors was mentioned as one of the main pillars of the new energy policy of Chile (Gobierno de Chile, 2014; Ministerio de Energía, 2015b, 2014).

For energy efficiency issues, the Energy Ministry collaborates with other ministries. Additionally, Energy Sustainability Agency (Agencia de Sostenibilidad Energética) is a non-profit public-private foundation that promotes energy efficiency by providing education and dissemination programs (Morgan et al., 2014). To reach the energy efficiency goals of 2035 and 2050, the government has progressively increased its budget for energy efficiency from USD 50 million in 2012 to USD 109 million in 2015 (IEA, 2018).

Table 2- 5:Energy policy instruments used in the world and in Chile to promote energy efficiency

<table>
<tr><th>Energy policy instruments used in the world to promote energy efficiency</th><th>Energy policy instruments status quo in Chile</th><th>Instruments to consider for energy sectors</th></tr>
<tr><td>Mandatory instruments
(laws, regulations, codes, and standards)</td><td rowspan="4">✓ Voluntary actions such as information and awareness campaigns
✓ Minimum energy performance standards
✓ Mandatory energy efficiency labelling for appliances
✓ Energy codes and efficiency standards for buildings (social housing and private residential buildings)
✓ Mandatory labelling for new light-duty vehicles</td><td>Mining and Industry:
➢ Regulations
➢ Codes and standards
➢ Certifications and labels</td></tr>
<tr><td>Economic instruments
(subsidies, taxes, and loan incentives)</td><td>Residential:
➢ Laws
➢ Regulations
➢ Codes and standards
➢ Subsidies
➢ Tax incentives
➢ Loans
➢ Certifications and labels</td></tr>
<tr><td rowspan="2">Voluntary instruments
(R&D, certifications and labels, governmental services)</td><td>Commercial and Public:
➢ Laws
➢ Regulations
➢ Codes and standards
➢ Loans
➢ Certifications and labels</td></tr>
<tr><td>Transportation
o Laws
o Regulations
o Codes and standards
o Subsidies
o Tax incentives
o Loans
o Certifications and labels</td></tr>
</table>

In the Chilean case, not only the residential sector but also the mining, transport, and industry sectors should be considered for energy efficiency actions to make significant contributions toward lowering global emissions as shown in Table 2-5. Chile has mandatory energy efficiency labelling for appliances, which is quite successful (Biblioteca del Congreso Nacional de Chile, 2012b). It also has energy codes and efficiency standards for buildings (social housing and private residential buildings) to increase energy performance. However, there are no regulations for non-residential and commercial buildings. Further, firewood is an important energy source for households in the south of Chile. Therefore, policies, regulations, and financial incentives are applied in order to support the efficient and clean use of firewood. In the Chilean industrial sector, besides MEPS, only voluntary actions are found in terms of energy efficiency. In the transport sector, an energy efficiency label for new light-duty vehicles has been mandatory since 2013. However, to promote energy efficiency successfully, besides voluntary instruments, mandatory and economic support mechanisms are required for specific sectors. More laws, regulations, codes, and standards must be investigated by the government for the industry, mining, and transport sectors and also economic and mandatory mechanisms for residential sector to reach the target of reducing energy consumption by 20% (against 2010) by 2025 (IEA, 2018).

2.6.2. Energy policy challenges for the future

Energy policy development is an iterative process. The developed policies need to be improved and adapted as lessons are learned and conditions evolve. Further, decision makers face many challenges when making adjustments in energy policy. In this section, some important challenges are discussed in terms of potential future energy policy actions.

Variable renewable energy: Rapidly developing renewable energy technologies and storage systems are significantly affecting the renewable energy contribution to energy planning. Decreasing costs will accelerate the implementation of renewable energy. Thus, incentives for renewable energy may not be needed, financial support must be limited, and new regulations should be considered depending on cost reduction of technologies. Chile is an example of the successful promotion of renewable energy without FITs, due to its high potential. However, cost reduction in energy storage and ocean-based energy production technologies can also be suitable for Chile, and new policies can be formed based on these developments in the future. One of the main challenges of variable renewable energy is that it needs to be properly coupled with flexible resources that can absorb their uncertainty and daily changes. This makes long-term planning and the design of effective energy markets and associated incentives a major challenge. Designing effective policy instruments to face this situation is of utmost importance (Bird et al., 2013; Miller and Cox, 2014; Stram, 2016).

Distributed energy resources: Technological progress, environmental concerns, and growing demand increase the number of distributed energy resources, which include small-scale power generation units and batteries, for example. Micro-turbines, PV panels, small-scale wind turbines, battery storage, and fuel cells are all considered as distributed energy resources. These resources must be integrated carefully by considering local energy markets and microgrids to provide an alternative for centralized energy production and long-distance energy transmission (Driesen and Belmans, 2006). Energy instruments like net metering must be redesigned for the many actors who would comprise small-scale producers. Chile has a long and narrow shape, which means that its geography requires long and expensive energy transmission. Thus, microgrids can further play an important role in providing reliable energy access for isolated communities. In particular, the south of Chile has various small islands where small communities live isolated from the main power grid (Mohd et al., 2008; Poudineh and Jamasb, 2014). Thus, policy instruments for the promotion of distributed energy resources can lead to substantial solutions for society.

Electric transportation and general electrification: In 2016, new registrations of electric cars reached a very high number, with over 750,000 sales worldwide since 2010. The global stock of electric cars exceeded 2 million vehicles in 2016; in 2015 this was approximately 1 million. Due to the transformation of electric transportation, oil consumption in the energy balance of countries is expected to be reduced. Thus, electricity demand will increase considerably by affecting resource procurement management (European Comission, 2017; IEA, 2017). Besides transportation, the revolution of electrification in heating and power will be another essential issue that concerns many sectors. Chile has a high oil consumer transportation sector. Also, heating from biomass is a common method in the countryside. Therefore, in order to keep up the electrification transformation, which is required to reduce GHG emissions, policies must be reformed to prepare for this adaptation and to extract the benefits from these important changes.

Demand response and aggregators: Instead of supplying more energy in high-demand times, demand itself can be managed to a certain extent through proper incentives and communication infrastructure to reduce consumption when it is more critical. This mechanism is called demand response, and it can significantly reduce emissions, provide for the efficient use of energy, and balance the operational costs. Especially in the integration of renewable energy, demand response is an effective management strategy to support the injections from these fluctuating resources. This approach could be emphatically considered for the Chilean industry and mining sectors to produce efficient future demand and supply planning. Thus, the design of proper policy instruments to generate value from the demand response potential is also a very important challenge (Albadi and El-Saadany, 2007; Poudineh and Jamasb, 2014; Su and Kirschen, 2009).

Climate change impact and resilience: Besides reliability, resilience is another essential concept to be considered in future energy systems. Due to climate change, some variations in the potential of hydro sources, as well as temperature and wind profile changes, are expected in future years (Panteli et al., 2017; Panteli and Mancarella, 2015). In addition to changes due to global warming, energy systems must be prepared for disasters such as tsunami, earthquakes, volcanic eruptions, and wildfires. Chile is a country with a high-risk potential for natural disasters. In recent history, it has had several high-magnitude earthquakes, tsunamis following earthquakes, the eruption of active volcanos, and wildfires, especially in summertime due to high temperature. All these types of disasters affect the secure energy supply. Thus, the Chilean energy system must be supported by policies to be prepared for quick changes and unexpected disasters.

2.7. Conclusion and Policy Implications

Oil, coal, natural gas, biomass, hydro, solar, and wind sources are the primary energy supplies of Chile. These sources are utilized in five main sectors in the country. Transport and industry have the major shares in total energy consumption, and mining activities in the northern regions are also heavily energy intensive. Chile mostly depends on imports for its domestic energy supply-almost 65% in the most recent years. It has noteworthy renewable energy potential for sources. The formation of the Ministry of Energy in 2010, dependence on imports for domestic energy supply, the significant transformation in the international energy market, global concerns about climate change, and the availability and competitiveness of renewable energy technologies have forced Chile to implement sustainable long-term energy planning and policies.

Promoting renewable energy and energy efficiency are popular ways for countries to reach their energy and environmental goals and for decarbonization and decontamination in the future energy matrix. FITs are the most popular renewable energy support mechanisms in the world. However, Chile became successful in promoting renewable electricity production without fiscal incentives or FITs. Nevertheless, encouraging the mining and industry sector with obligatory regulations, using public finance for the residential sector, and mandatory economic instruments for the transport sector can be useful to increase the renewable energy share in all energy sectors.

Adoption of energy efficiency in several energy sectors is another substantial matter to achieve a sustainable energy future. Chile has mandatory energy efficiency labelling for appliances, energy codes, and efficiency standards for social housing and private residential buildings. However, there are no regulations for non-residential and commercial buildings and the efficient and clean use of firewood. In the Chilean industrial sector, only voluntary actions are found. In the transport sector, an energy efficiency label for new light-duty vehicles has been mandatory since 2013. Chile has mostly voluntary support mechanisms for energy efficiency.

Nonetheless, mandatory and economic support mechanisms are also necessary for specific sectors. More laws, regulations, codes, and standards must be implemented by the government in the industry, mining, and transport sectors to reach the national target. The combination of renewable energy instruments with energy efficiency instruments can produce a substantial impact. This work can provide meaningful thought for decision makers while they develop long-term sustainable energy plans so that Chile can reach energy and environmental goals. Further studies are planned to develop a long-term demand and supply model of the Chilean energy sector by creating several scenarios with different energy policy instruments and evaluating the impacts of these instruments on energy and environmental targets.

2.8. Summary of the chapter

Section 2 includes a broad overview of the energy sector and review of the Chilean energy policy development and environmental targets with emphasis on recent years. Also, it proposes an assessment about existing and required energy policy instruments for Chilean energy sectors by considering the promotion of renewable energy and energy efficiency and analyses the associated potential challenges. With this section, energy sector and energy policy development of Chile is reviewed in detail. After that, in order to understand current policy in Chile, the research is conducted in the following section. Section 3 contains an assessment of the renewable energy deployment in Chile and analysis of current renewable energy policies by using a multi-criteria decision method (MCDM) in which the policy assessment criteria are weighed by Chilean energy experts.

3. EVALUATION OF RENEWABLE ENERGY DEPLOYMENT AND POLICY ANALYSIS FOR CHILE

Abstract

The combination of various energy policies aimed at stimulating renewable energy and several encouraging global factors such as technological innovations and cost reductions have made renewable energy technologies competitive towards de-carbonization and combating climate change. Assessment of renewable energy promotion and existing policy analysis is vital to comprehend the current situation and to shed light on developing future policies. Motivated by this, this research aims to assess the renewable energy deployment in Chile and analyze current renewable energy policies by using a multi-criteria decision method (MCDM) in which the policy assessment criteria are weighed by Chilean energy experts. The results show that the capacity of solar photovoltaic and wind power technologies showed a major growth after 2013 and the policy effectiveness index for solar and wind are obtained higher than biomass, mini-hydro and geothermal. Additionally, the multi-criteria analysis results showed that a legislative policy, which includes a target for renewable energy capacity, was considered as the most effective policy among all related alternatives. Moreover, subsidies and regulations including technical standards and a certification system to encourage installing solar water heaters for the residential sector were found as effective policies in the MCDM analysis.

3.1. Introduction

Renewable energy showed significant development all around the world in recent years. Technological development and cost reduction in the renewables are supported by energy policies globally towards low carbon transition, although this evolution is not homogeneous across the world due to some barriers. Global electricity generation from renewable energy reached almost 26.5% in 2018, as presented in Figure 3-1. In parallel with the developments in the world, electricity generation share from renewables in Chile also increased significantly with a rise from 15% to 19.92% between 2015 and 2018, respectively.

Chile mainly depends on imports for its domestic energy supply; the share was approximately 65% in 2016, and the total primary energy supply reached almost 32 million tons of oil equivalent in 2016. Oil is the main energy source, followed by biomass (mainly firewood), coal, natural gas, and hydro, correspondingly (Simsek et al., 2018a). Chile has remarkable potential for renewable energy, such as solar, wind, hydro, geothermal, ocean, and biomass sources. The northern region has one of the best solar energy potentials in the world to generate electricity due to its dryness and clear sky (Escobar et al., 2015, 2014). In parallel to the world, Chile has commenced numerous actions for climate change adaptation since 2011, which can be noticed from the following government-led studies: three-phased MAPS-Chile project, the Energy Agenda, National Energy Balance, Road Map, Energy 2050, and Energy Route 2018 (MINERGIA, 2015; Ministerio de Energía División de Prospectiva y Política, 2018; Ministerio del Medio Ambiente (Mitigation Action Plans and Scenarios), 2011; Ministry of Energy, 2014a, 2014b). In most of these studies, the integration of renewable energy and energy efficiency are explicitly mentioned for decarbonization in the future energy matrix in Chile (Simsek et al., 2018a).

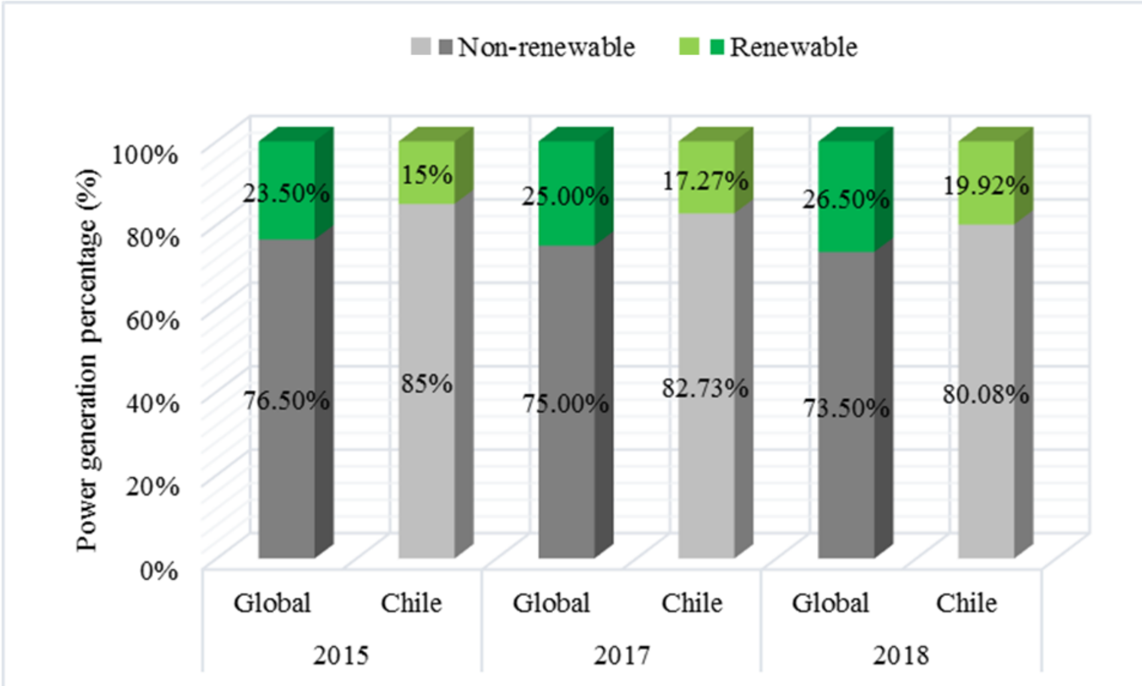


Figure 3- 1:Renewable and non-renewable electricity generation for the world and Chile Source: The figure was reconstructed based on References (Comisión Nacional de Energía (CNE), n.d.; IRENA et al., 2018; Renewable Energy Policy Network for the 21st Century (REN 21), 2018).

The Chilean Ministry of Energy was created in 2010 by being separated from the Ministry of Mining (Biblioteca del Congreso Nacional de Chile, 2012a; Congreso Nacional de Chile, 2009). Activities related to long-term sustainable energy planning have accelerated after the establishment of the energy ministry. When looking at the current energy situation in Chile, significant developments in energy policy can be seen between 2011 and 2018 (Simsek et al., 2018a). MAPS-Chile can be considered as the first project that developed projections and mitigation action plans to reduce greenhouse gas emissions in Chile (Gobierno de Chile, 2013, 2012; Ministerio del Medio Ambiente (Mitigation Action Plans and Scenarios), 2011). In those years, besides governmental studies, energy-related actors have come together and performed some studies for the long-term electricity planning in which several scenarios were proposed for electricity expansion for the central and northern interconnected systems of Chile until 2030 (Escenarios energeticos, 2018). 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 (Ministerio de Energía, 2014). 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 (Comité Consultivo de Energía 2050, 2015). In 2017, Chile ratified the Paris Agreement and committed to developing 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 MW_{th} (The Committee of Ministers for Sustainability and Climate Change, 2015). After the elections in 2017, there was a change in government and a new study *Energy Route 2018-2022* was published to present the new government´s energy approach. The main axes of the new energy route towards sustainable energy were defined with this study as follows: energy modernization, energy with a social seal, energy development, efficient transportation, low energy emissions, energy efficiency, and energy education and training (Ministerío de Energía, 2018).

Energy policy must comply with the national circumstances considering political consensus, clear long-term vision, stable institutions, leadership, and stakeholders engagement (Arababadi et al., 2017; Elizondo Azuela and Barroso, 2011; Simpson and

Mcnamara, 2011). In order to have efficient policies to promote renewable energy, country-specific assessment should be conducted to understand the impact of factors (current policy and global factors) on renewable energy deployment. Also, existing policies should be assessed to check if the planned objectives are met and if it is necessary to regulate or eliminate the policy (Bustamar et al., 2017).

Motivated by this, this research aims to assess the renewable energy deployment in Chile and analyze the current renewable energy policies by considering the policy assessment criteria determined by Chilean energy experts by using multi-criteria decision method. This paper has five main contributions to the literature: 1) perform a systematic analysis to collocate energy-related laws and policies in Chile 2) evaluate the renewable energy promotion in Chile 3) determine assessment criteria from literature to assess energy policies 4) obtain criteria weights by consulting experts in the energy sector 5) conduct multi-criteria decision analysis to the existing energy policies to understand the best policies based on experts´ preferences. Additionally, this research includes a methodology which has not been used so far to analyze energy policy in Chile in the literature. The objectives of this research are as follows:

- Assessing the renewable energy deployment in Chile by considering global factors and current energy policies
- Developing a set of criteria to evaluate renewable energy policies and obtain criteria weights for policy assessment by expert opinions
- Applying the Multi-Criteria Decision Analysis (MCDA) method to understand the energy policy preference and developments in Chile based on the chosen criteria

The paper is organized as follows: Section 1 is an overview, providing a summary of energy policy developments in Chile, aims and objectives, the significance of the research and the scope. Section 2 provides the methodological approach including a broad review of energy policy and assessment of renewable energy deployment and multi-criteria decision analysis. Section 3 presents results and discussion including a summary of energy-related laws and policies, assessment of renewable energy deployment in Chile, and current policy evaluation with MCDM. Finally, Section 4 concludes the paper.

3.2. Methodology

The methodological approach in this research is based on a broad systematic review of energy laws and policies, assessment of renewable energy deployment, and multi-criteria decision analysis of current energy policies as illustrated in Figure 3-2. Each stage is explained in additional detail within the subsequent sections.

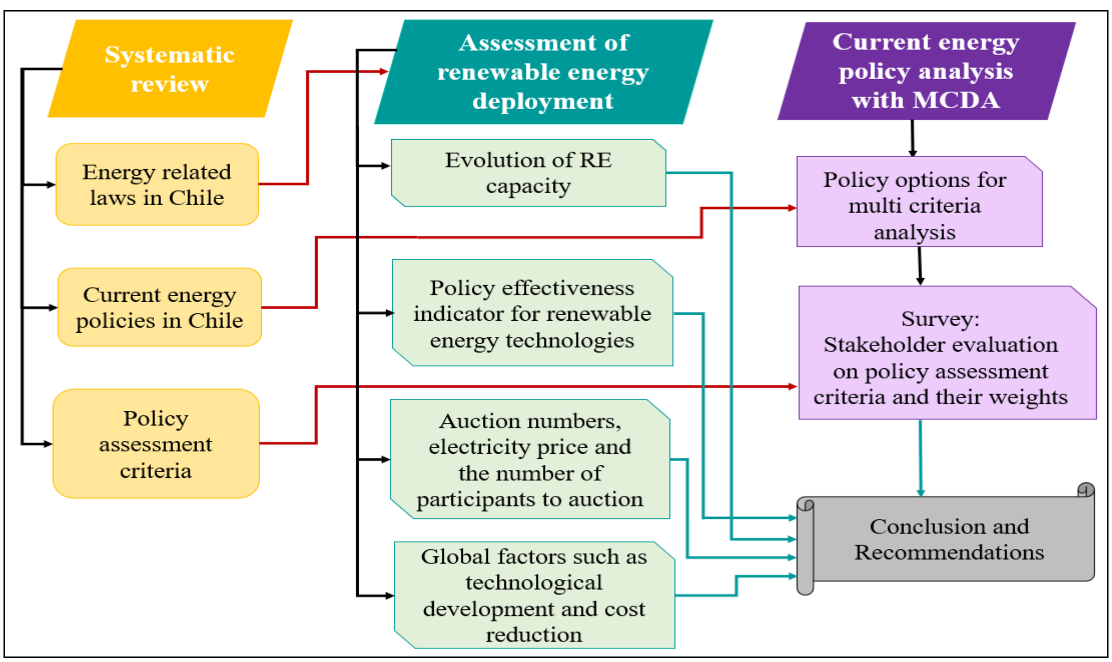


Figure 3- 2:Flowchart of the methodological approach

3.2.1. The summary of a systematic review

The first stage of the research is the review of energy laws and policies in Chile. This step aims to collect and categorize energy-related data for further policy analysis. Also, the policy assessment criteria for additional analysis were obtained from a literature review. Scientific and formal databases and other search engines were utilized to reach relevant sources such as governments reports, government-related documents, news articles and peer-reviewed articles. Moreover, the reports of many international organizations were considered to collect appropriate global and countrywide energy data. Mostly, references from the year 2000 onwards were taken into account to gather quantitative or qualitative information relating to the study objectives. After obtaining sources about the Chilean energy sector, filtration was carried out with the keywords: renewable energy, laws, policies, energy efficiency, low carbon, environment, etc. to list related energy laws and policies. The outputs of the comprehensive systematic review are essential energy laws of Chile, significant energy policies, and energy policy assessment criteria to be utilized later in the analysis.

3.2.2. Assessment of renewable energy deployment

In the literature, renewable energy policy studies considering developed countries such as the Czech Republic, Germany, the Netherlands, Spain, South Korea, Switzerland, Taiwan, and the UK can be found (Chen, 2011; European Environment Agency, 2014; Shokri and Heo, 2012). Besides developed countries, studies related to developing countries such as China, Iran, Brazil, India, Turkey, and Sri Lanka also exist in the literature (Abotah, 2014; Elizondo Azuela and Barroso, 2011; Hafeznia et al., 2017; Liu et al., 2018; Nath, 2008; Si et al., 2018; Thapar et al., 2016). In addition to studies related to renewable energy policy, the effectiveness of different policies are studied by many researchers for several policy instruments such as; subsidies to increase energy efficiency, and lower fossil fuel consumption (Si et al., 2018), carbon tax, renewable portfolio standards (Liu et al., 2018), addition of new generation and capacity (Hafeznia et al., 2017; Thapar et al., 2016), market growth (Elizondo Azuela and Barroso, 2011), renewable purchase obligation (Nath, 2008), tax credits(Abotah, 2014), energy efficiency (Aydin and Brounen, 2019; Bertoldi and Mosconi, 2015; Bratanova et al., 2015; Pollitt et al., 2017). There are also few studies about Chilean energy policy assessment about carbon tax (Benavides et al., 2015) and mandatory energy efficiency labelling (IEA, 2018).

In this study, in order to assess the renewable energy deployment in Chile, evolution of renewable energy capacity (Elizondo Azuela and Barroso, 2011), policy effectiveness indicator (PEI) for specific renewable energy technologies (European Environment Agency, 2014, 2011; Puig and Morgan, 2013; Ragwitz et al., 2006), the relation between number of auctions, the resulting electricity price, and the number of participants in such auctions (IEA, 2018), and finally globally technological development and price reduction in renewables were discussed. In the literature, the Policy Effectiveness Indicator (PEI) is defined to measure the effectiveness of policies and it is defined as *a percentage of the remaining production potential that can be realized by the end of the pre-defined medium-term period as measured at the start of that period* as formulated in equation (3-1) (European Environment Agency, 2014, 2011; Puig and Morgan, 2013; Ragwitz et al., 2006).

$$E_n^i = \frac{G_n^i - G_{n-1}^i}{POT_t^i - G_{n-1}^i} \qquad (3\text{-}1)$$

G_n^i is production by renewables technology i in year n;

POT_t^i is the total production potential of technology i in year t;

t is the year (such as 2030, 2050).

3.2.3. Multi-criteria decision analysis

In this section, multi-criteria decision methods, policy evaluation criteria, and criteria weights were described in details. Multi-criteria decision methodology is a well-known technique to make a decision based on the comparison of alternatives. The main objective is to select the alternative/option having the highest results based on the chosen evaluation criteria. Criteria can be both quantitative and qualitative to be evaluated by decision-makers (Daim et al., 2013a; Simsek et al., 2018c).

MCDMs have common stages in the process of decision making as follows: (1) structuring the decision process, alternative selection and criteria formulation, (2) determination of criteria weights, (3) creation of evaluation matrix, (4) selection of a suitable method, and (5) calculation of a final ranking and making a decision among the alternatives (Daim et al., 2013a; San Cristobal Mateo, 2012). MCDM can be categorized into two main groups according to problem-solving techniques: multi-objective decision-making (MODM) and multi-attribute decision-making (MADM). MODM is used to optimize conflicting objectives with mathematical programming, and there might be several solutions. On the other hand, MADM is utilized to identify an ideal alternative or to rank all options/alternatives (Daim et al., 2013b; Kumar et al., 2017; Simsek et al., 2018c). The most commonly used methods are analytical hierarchy process (AHP), weighted sum method (WSM), preference ranking organization method for enrichment evaluation (PROMETHEE), the elimination and choice translating reality (ELECTRE), the technique for order preference by similarity to ideal solutions (TOPSIS) and, multi-attribute utility theory (MAUT) (Daim et al., 2013a; Simsek et al., 2018c; Wang et al., 2009).

WSM method was utilized to conduct MCDA in this research. The assessment criteria were also obtained from the literature, and their importance was acquired by consulting experts´ opinions via a survey. The survey was carried out via google survey link which also included information letter and consent form. Before communicating the participants, ethics approval from the research ethics committee of the university was completed to conduct a survey. Thirty participants were chosen from the government (ministries and energy-related agencies), academy (universities and research centres) and industry (private energy companies) (details at Table A1, Appendix A) and the link of the survey was sent to them to participate. First, the participants´ opinion about the importance of each criterion was asked to assess a policy. Then, they evaluated the significance of sub-criteria in each group.

For the policy assessment, four main criteria and sixteen sub-indicators were chosen as presented in Table 3-1 and explained as follows:

- *Relevance to sustainability:* Policies are assessed how they are related to sustainability by considering sub-criteria:
- having the potential to reduce emission, contribution to the low carbon economy, having a clear long-term vision, and contribution to the independence of energy supply (CIPPEC, n.d.; Simpson and Mcnamara, 2011).
- *Efficiency and Efficacy:* By taken into account sub-criteria: easy to implement and control, requires less institutions to put into practice, requires less time to implement, encourages local and global investors feasible for implementation and

control, the efficiency of the policy is evaluated (CIPPEC, n.d.; IEA-RETD (Renewable energy technology development), 2015; Nicholls et al., 2014; UCL, 2014).

- *Impact:* With this criterion, easiness to measure the impact, including quantitative targets, having an equal impact on the applied region, having long-lasting effect and benefits are assessed (CIPPEC, n.d.; Nicholls et al., 2014).
- *Cost:* In the literature, the cost is also mentioned as policy assessment criteria to evaluate if a policy has a feasible cost for government or cost of implementation for the producer, investors. Cost-effective for government and profitable incentive for the producers, investors were also considered during the assessment of policies (Benitez, 2012; IEA, 2018).

Table 3- 1:Policy assessment criteria (from literature review)

Relevance to sustainability	**Efficiency and Efficacy**	**Impact**	**Cost-effectiveness**
Having the potential to reduce emission	Easy to implement and control	Easy to measure the impact	Cost-effective for the government
Contribution to the low carbon economy	Requires less institutions to put into practice	Includes quantitative targets	The profitable incentive for producers, investors etc.
Having a clear long-term vision	Requires less time to implement	Having an equal impact on the applied region	
Contribution to the independence of energy supply	Encourages local and global investors	Having a long-lasting effect and benefits	

Furthermore, experts in the energy field from Chile were contacted via a survey to assess the policy evaluation criteria based on their experiences. After the survey, the weights of four main assessment criteria and fourteen sub-criteria were obtained, as shown in Figure 3-3. Between four main categories, relevance to sustainability was chosen as the most important criterion with 30% weight. Besides, efficiency and efficacy, impact, and cost indicators followed *relevance to sustainability* criterion with the weights: 25%, 20%, and 25%, respectively. When sub-indicators are considered, it can be seen from the figure that experts mostly chose the indicators: having potential to reduce emission, contribution to the low carbon economy, easy to implement and control, includes quantitative targets, cost-effective for government, and profitable incentive for producers, investors, etc., as essential criteria to evaluate current energy policies in Chile.

In the following section, results and discussion about analyses were presented. Summary of energy-related laws and policies, the effectiveness of energy laws and current policy assessment with MCDM can be found in the results and discussion section.

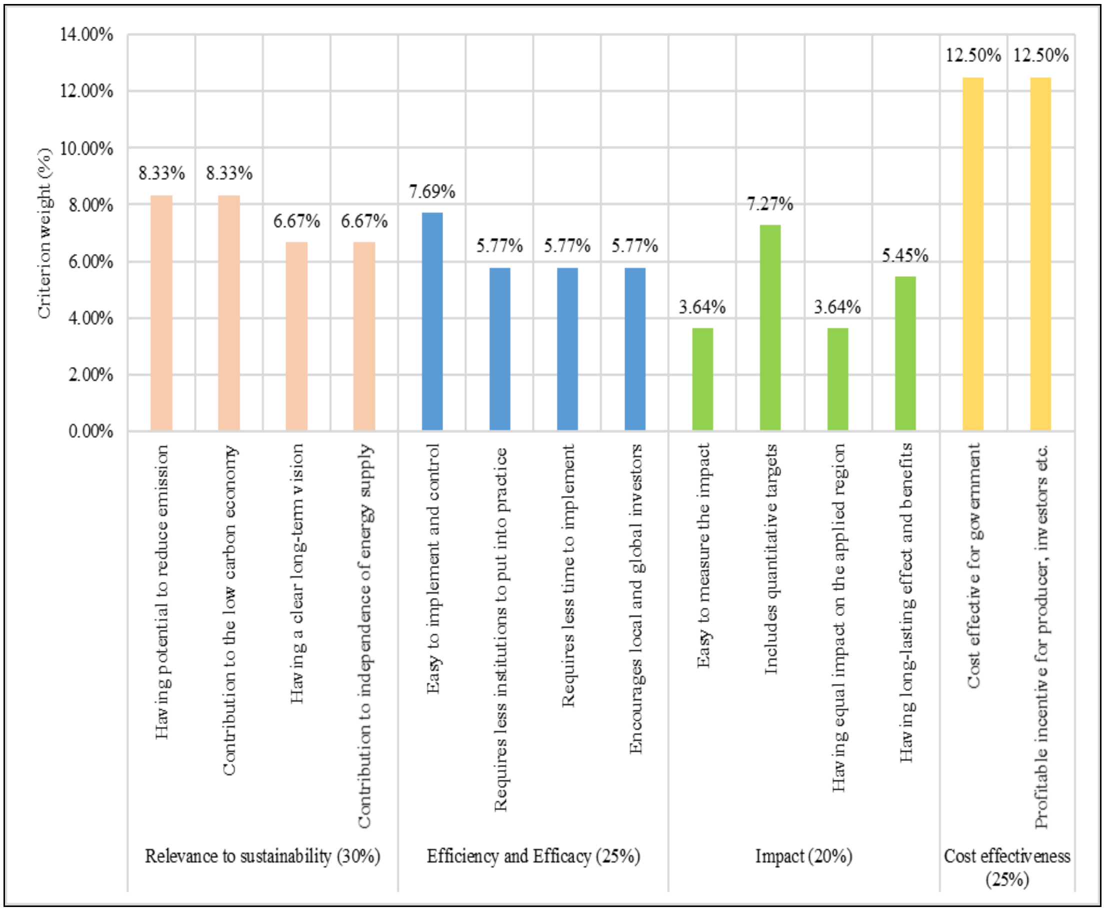


Figure 3- 3:Policy assessment criteria weights considered in the analysis (obtained from the survey)

3.3. Results and Discussion

3.3.1. Summary of energy-related laws and policies

After a broad review and filtration, sixty-five renewable energy-related laws and policies were obtained as presented in Appendix A (in Table A2). In order to discuss their impact, seven laws related to renewable energy and low-carbon emission transition were selected as listed in Table 3-2. Also, these laws which are enacted between the years 2008- 2016 and explicitly mentioned in international reports were chosen to show the significant changes in the Chilean energy system.

Between the years 2008 and 2016, Chile enacted laws to promote renewable energy, to regulate environmental assessment, to set renewable energy targets, to encourage small renewable energy systems, to reduce carbon emissions, and to support grid extension for renewable energy. For this research, Law 20.257 (renewable electricity generation), Law 20.417 (environmental law), Law 20.698 (renewable electricity target and public auction), Law 20.571 (net billing), Law 20.780 (carbon taxes), Law 20.018 (public tendering), and Law 20.936 (grid expansion for renewables) were chosen to be focused as listed in Table 3-2.

Table 3- 2:Relevant laws for the energy sector in Chile

Year	**Relevant laws for the energy sector**
2008 (enacted) 2013 (amended)	The Non-Conventional Renewable Energy Law (“NCRE” Law 20.257) was enacted in 2008 and amended in 2013 to achieve future energy requirements for electricity generation from renewable sources such as geothermal, wind, solar, tidal, biomass and small hydroelectric plants (Ministerio de Economía, 2013).
2010 (enacted) 2012 (amended)	The General Environmental Law (Law 20.417) includes the environmental assessment service and the environment superintendence. Also, it establishes the environmental assessment system which sets emission/quality standards and creates prevention and decontamination plans (Ministerio del Medio Ambiente y Gobierno de Chile, 2010).
2013	The so-called “20/25 Law” (Law 20.698) aims to produce 20% of Chile’s electricity from renewable sources by 2025, excluding hydropower plants over 20 megawatts (MW). This law also introduces a new public auction system (Ministerío de Energía, 2013).
2012 (enacted) 2014 (amended)	The net billing law (Law 20.571) mainly allows users to sell their surplus electricity directly to the grid (electricity distributor) at a regulated price. This law establishes the connection framework conditions of small power systems (up to 100 kW) to the distribution grid (MInisterio del Interior y Seguridad Pública, 2014).

2014	In October 2014, Chile enacted the first climate pollution tax in South America (Law 20.780). This tax improvement forces an annual tax on emissions from boilers and turbines with a thermal input of at least 50 MW (Ministerio de Hacienda, 2014).
2005 (enacted) 2015 (modified)	The so-called “Short Law II” (Law 20.018, Ley Corta II), last modified in 2015, improves competition conditions in generation activities. It allowed power generators, including renewable energy producers, to sign long-term supply contracts with distribution companies, awarded through a non-discriminatory public tendering process instead of using the price regulated by the CNE (Ministerio de Economía, 2015).
2016	The Transmission Law (Law 20.936) established the new national transmission system to support the grid expansion and the interconnections between the transmission grids, increase competition in the electrical market and modifies the transmission toll payments to encourage renewable electricity generation (Ministerío de Energía, 2016).

Additionally, between sixty-five current energy laws and policies of Chile listed in Appendix A (in Table A2), some energy policies were chosen to be utilized in the further MCDM analysis. Due to assessing laws separately, only fifty-one policies remained on the list. Also, some policies were repeating, and some had a modification in the following years. Finally, the policies between the years 2005 and 2017 were considered for multi-criteria analysis. Therefore, it was determined to have twenty-eight policies in the analysis. Once the policies were selected, they were classified into three groups monetary, regulatory and legislative as presented in Table 3-3. Policy classification aims to analyze different policies within the group since each policy has distinct objectives when they are implemented. The monetary policy is money or economy-related actions taken by the government. The regulatory policy includes official acts with regulations by the government to achieve an objective. The legislative policy is statutory procedures that are likely to be enacted as law.

It can be noted that the chosen policies in Chile are mostly legislative and monetary policies, and a few numbers of regulatory policies also exist as listed in the table. After that, these policies are evaluated with the policy assessment criteria by using MCDM, and the results are presented in the following section (Section 3.3).

Table 3- 3:Current energy policy in Chile

Policy no	Date		*Type*
P1	**2005**	Partially subsidizing pre-feasibility and pre-investment studies for renewables	*Monetary*
P2	**2007**	The minimum energy performance standard for the building envelope to contribute energy efficiency	*Legislative*
P3	**2007**	Fiscal incentives for biodiesel and bioethanol (transportation usage) include an exemption from fuel tax (and alcohol tax in the case of bioethanol)	*Monetary*
P4	**2008**	Technology-specific support for concentrated solar power including a subsidy for up to 50% of the costs of the project	*Monetary*
P5	**2008**	Regulations to allow the blending of bioethanol and biodiesel with gasoline and diesel (in transportation) respectively at 2% or 5%	*Regulatory*
P6	**2009**	Regulations for solar water thermal including technical standards and certification systems	*Regulatory*
P7	**2010**	Providing tax breaks for businesses and end-users for installing water-heating solar thermal panel	*Monetary*
P8	**2011**	Energy label for residential buildings, with categories that ranged from “A” (highest efficiency) to “E” (lowest efficiency), with “E” corresponding to the minimum standard for the building envelope	*Legislative*
P9	**2012**	A net metering scheme for consumers under-regulated electricity tariffs, which is applied to renewable energy and cogeneration systems of up to 100kW	*Legislative*
P10	**2012**	Subsidizing transmission lines for renewable energy projects	*Monetary*
P11	**2012**	Subsidies of up to 90% of installation costs of PV pumping to farmers	*Monetary*
P12	**2012**	Financial support for the establishment of the solar energy research centre (R&D)	*Monetary*
P13	**2013**	Mandatory energy efficiency label for new light-duty vehicles	*Legislative*
P14	**2013**	Technology neutral auction system to complement the existing quota obligation	*Legislative*
P15	**2013**	Technology-specific support to provide a clear regulatory framework for geothermal exploration and development	*Monetary*
P16	**2014**	The electricity generated by hydropower projects under 20MW are eligible for quota obligation	*Legislative*
P17	**2014**	Fiscal incentives for solar water heating, as well as providing subsidies for the installation of solar water heaters in the reconstruction of disaster-affected areas	*Monetary*
P18	**2014**	Regulation on biomass usage to increase quality standards	*Regulatory*

P19	**2014**	Co-financing for renewable energy projects for productive uses in agriculture and forestry	*Monetary*
P20	**2014**	Subsidies to encourage installing solar water heaters for residential water heating	*Monetary*
P21	**2015**	A mandatory energy efficiency label for firewood stoves and pellet heaters	*Legislative*
P22	**2015**	The significant target for renewable energy capacity increase (70% of new capacity renewable energy installation target between 2015 and 2050)	*Legislative*
P23	**2016**	Auctions for public lands with a high resource potential for the construction of renewable-energy projects in several locations	*Legislative*
P24	**2016**	Loan for renewable energy projects for banking	*Monetary*
P25	**2017**	Energy efficiency seal (with three categories: bronze, silver, and gold) to recognize energy-efficient companies of all sizes, including industrial companies	*Legislative*
P26	**2017**	Energy efficiency label for medium-duty vehicles up to 3 600 kilograms (kg), and to electric and hybrid vehicles	*Legislative*
P27	**2017**	Subsidizing the replacement of taxis with higher-efficiency vehicles and the introduction of electric buses	*Monetary*
P28	**2017**	Regulations on biogas plant safety	*Regulatory*

3.3.2. Assessment of renewable energy deployment in Chile

Figure 3-4 presents the increase in renewable energy capacities in the Chilean energy system between the years 2008 and 2018 for the following technologies: solar PV, mini-hydro, geothermal, wind, and biomass. In addition to capacity increase, the renewable energy-related laws are presented in the figure based on the year of implementation and modification. With the Non-Conventional Renewable Energy Law enacted in 2008, the promotion of geothermal, wind, solar, tidal, biomass and small hydroelectric plants electricity production was explicitly promoted (Ministerio de Economía, 2013). The General Environmental Law includes the environmental assessment of the energy project, in which renewable energy technologies have advantages when compared to fossil technologies (Ministerio del Medio Ambiente y Gobierno de Chile, 2010). The “20/25 Law”, enacted in 2013, set a target to produce 20% of Chile’s electricity from renewable sources by 2025. Also, with this law, a new public auction system was announced to allow renewable energy technologies to compete with other projects (Ministerío de Energía, 2013). The net billing law promotes the distributed generation and mainly allows users to sell their surplus electricity directly to the grid at a regulated price. It allowed small PV and wind power systems (up to 100 kW) to grow very quickly (MInisterio del Interior y Seguridad Pública, 2014). Carbon tax law applies an annual tax on emissions from boilers and turbines with a thermal input of at least 50 MW, which made renewables more advantageous (Ministerio de Hacienda, 2014). Short Law II improved competition conditions between power generators, including renewable energy producers (Ministerio de Economía, 2015). Further, the transmission law established the new national transmission system to support grid expansion and encourage renewable electricity generation (Ministerío de Energía, 2016).

As Figure 3-4 shows, the total renewable energy capacity increased in the Chilean energy system in the last eight years. It can be seen that solar and wind technology had more increase than biomass and mini hydro. Also, the capacity of solar PV and wind technologies showed significant increase after 2013. Moreover, a government study for long term energy policy showed that solar and wind technologies have high social acceptance in several Chilean communities (Ministry of Energy, 2015). Besides utility-scale PV capacity growth, it was explicitly reported that distributed generation PV solar capacity increased essentially after 2012 in remote regions due to net billing law (Law 20.571) which allows the connection to small power systems to the distribution grid by selling their surplus energy (Comisión Nacional de Energía (CNE), 2018; División Energías Renovables, 2016).

Additionally, the capacity of mini-hydro plants was expanded in the last years; however, it is not as significant as solar and wind technologies. Although Chile has potential for hydropower and the laws tend to help to promote this technology (the non-conventional renewable energy law (“NCRE” Law 20.257), general environmental laws (Law 20.417), and 20/25 Law (Law 20.698)), the environmental concern and social opposition to large hydroelectric power projects in Chile affected the hydroelectric share in the generation mix. A few years ago, the Chilean government had to cancel the project “HidroAysen” due to major social opposition. Further, after that happened, the social opposition to hydroelectricity from environmental groups and indigenous communities even increased (IEA, 2018).

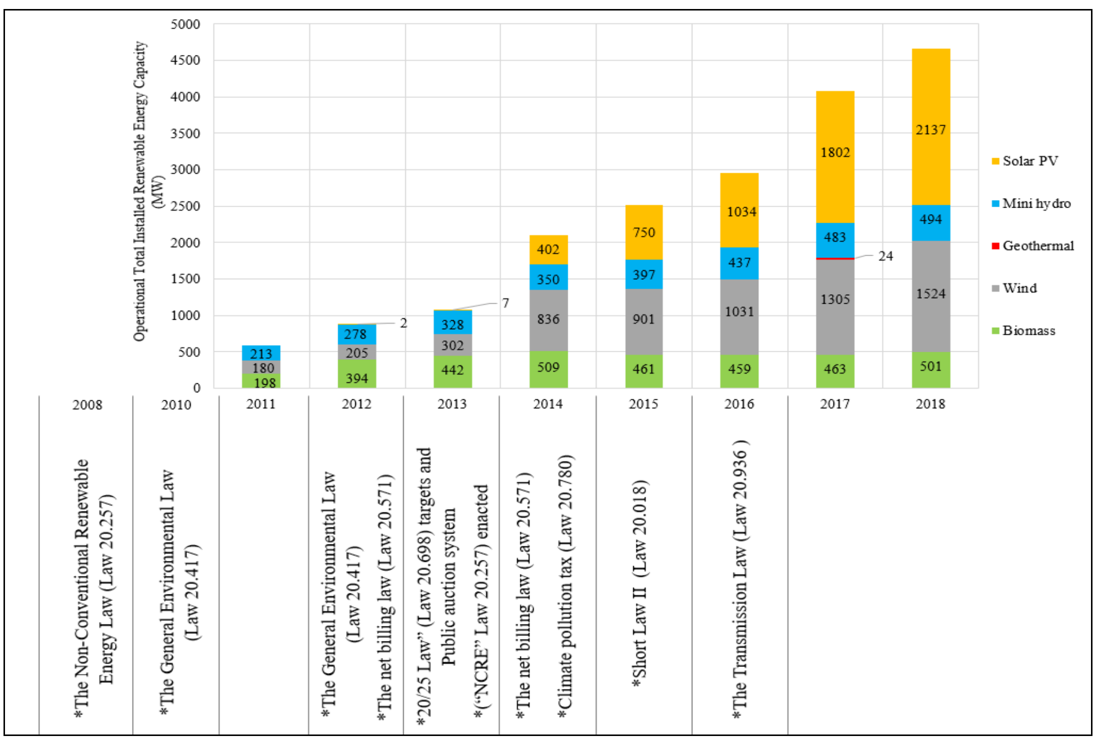


Figure 3- 4:Renewable energy capacity increase in the Chilean energy system between the years 2008 and 2018. Source: The figure was constructed based on the data in References (Comisión Nacional de Energía (CNE), n.d.)

Besides, the capacity of biomass technology had a growth until 2014, and after that, it showed irregular increases and decreases. The biomass usage is mainly based on traditional biomass in Chile. Thus, in order to have essential biomass capacity increase, clean biomass technologies should be promoted by laws. On the other hand, geothermal technology could not be promoted enough, as shown in the figure. Some added capacity appeared in 2017. However, such capacity was not sustained in the following years. More specific laws and policies are required to increase the capacity of geothermal technology in Chile. Also, when geothermal is compared to other technologies, it requires more financial support and technological developments due to having expensive resource exploring and costly production.

In addition to the evaluation of renewable energy capacity increase and related laws, the policy effectiveness indicator (PEI), as defined in the IEA and UNEP work (Puig and Morgan, 2013), was calculated for each renewable energy technology for each year with the equation as mentioned in section 2.2. The PEI indicates *to what extent the remaining gap to a future target for renewable energy sources is covered per year* (European Environment Agency, 2014). It is important to emphasize that PEI measures only the effectiveness of overall renewables policy; it does not measure the effect of individual policies. Also, it does not provide any direct understandings into why a specific policy is successful or ineffective. However, it is an essential indicator to compare and understand the policy effectiveness of different technologies. Renewable energy generation values for Chile were obtained from governments monthly reports (Comisión Nacional de Energía (CNE), n.d.), and the targeted generation values for 2050 were acquired from the Chilean Energy Road Map 2050 (Comité Consultivo de Energía 2050, 2015). Calculated PEIs for biomass, wind, solar, mini-hydro and geothermal were presented in Figure 3-5. According to this figure, renewable energy-related laws implemented between 2012 and 2017 could have the best impact on promoting solar energy technologies due to its positive PEIs. Although the years 2012 and 2013 present lower effectiveness index, in the following years significant PEI can be seen for solar technology. Also, policies to promote wind and mini-hydro technologies could be less effective than solar energy due to having lower PEIs. Energy policy to promote biomass also seems insufficient with its irregular PEIs for different years.

In conclusion, for wind, mini-hydro and geothermal in particular, higher policy effectiveness is required to meet the 2050 targets set up in national Chilean energy plans. On the other hand, PEI for biomass should be interpreted differently from other renewable sources due to the significant amount of traditional biomass usage in Chilean energy sectors as mentioned above. In order to increase PEI for biomass, promotion of clean biomass technologies should be considered in the policies and laws to ensure a sustainable biomass supply. Also, PEI for geothermal is only seen for 2016 and 2017, which means that not any efficient policies exist to promote geothermal technology before these years, which is explained due to having expensive resource exploring and costly production.

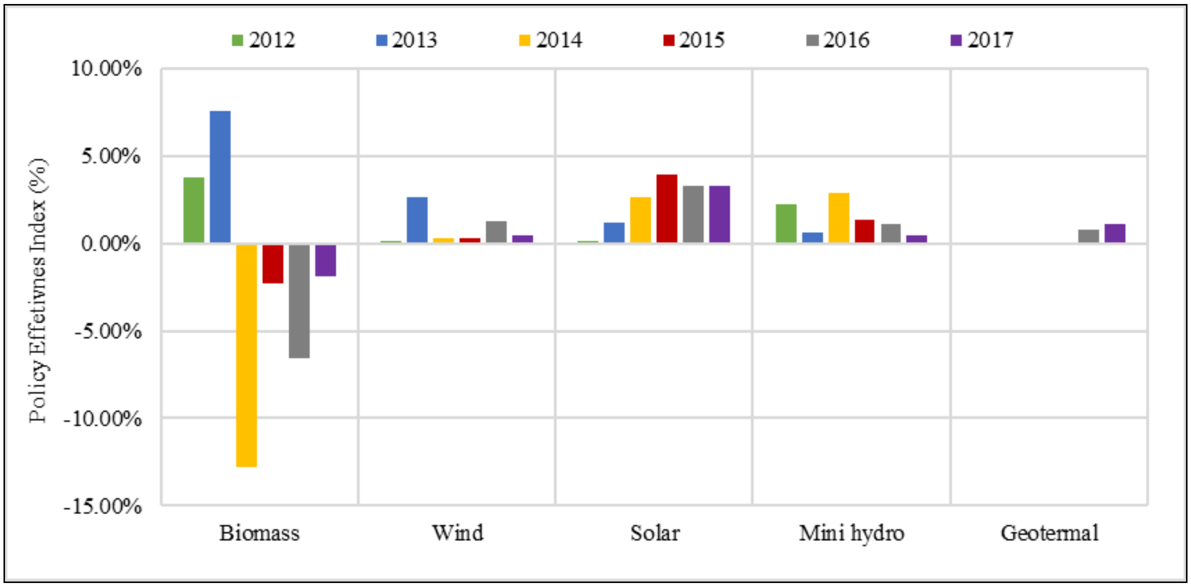


Figure 3- 5:Yearly policy effectiveness indicator for renewable energy technologies between 2012 and 2017 Source: The figure was constructed based on the data in References (Comisión Nacional de Energía (CNE), n.d.) and (Comité Consultivo de Energía 2050, 2015).

In Figure 3-6, the relation between the energy laws, auction volume, electricity price and the number of tender participants in Chile was illustrated. Although renewable energy promotion laws were enacted since 2008, the bid prices reduced after 2013. Because the effectiveness of some energy policies to promote renewables is only understood with time. The auction systems are such policies, and they have the potential to provide low-cost renewable energy capacity in time (Elizondo Azuela and Barroso, 2011). Also, it is observed that there is no direct relation between the tender volume and the resulting prices. For instance, the years 2010 and 2017 had a similar tender volume; nevertheless, the bid price was different and reduced significantly. Global technological development, decreased costs of PV technology, more participants in the following years and a more competitive market can also be possible reasons for the reduction of the bid price.

Moreover, after 2010, it is clear to see the opposite relation between auction participant number and bid prices. When the participants increased, the price went down until 2017. The possible reason could be the contribution of non-conventional renewable energy law, 20% renewable electricity target, and the new public auction law which allowed renewables to compete with conventional technologies. Besides, the number of auction participants significantly increased after 2015 in which Short Law II (Law 20.018) was enacted, and it started to improve competition conditions including renewable energy producers. Also, after the Transmission Law was passed to encourage renewable electricity generation, numerous PV company participated in the 2017 auction. Thus, the auction price reached the lowest point in 2017 by the contribution of PV technologies.

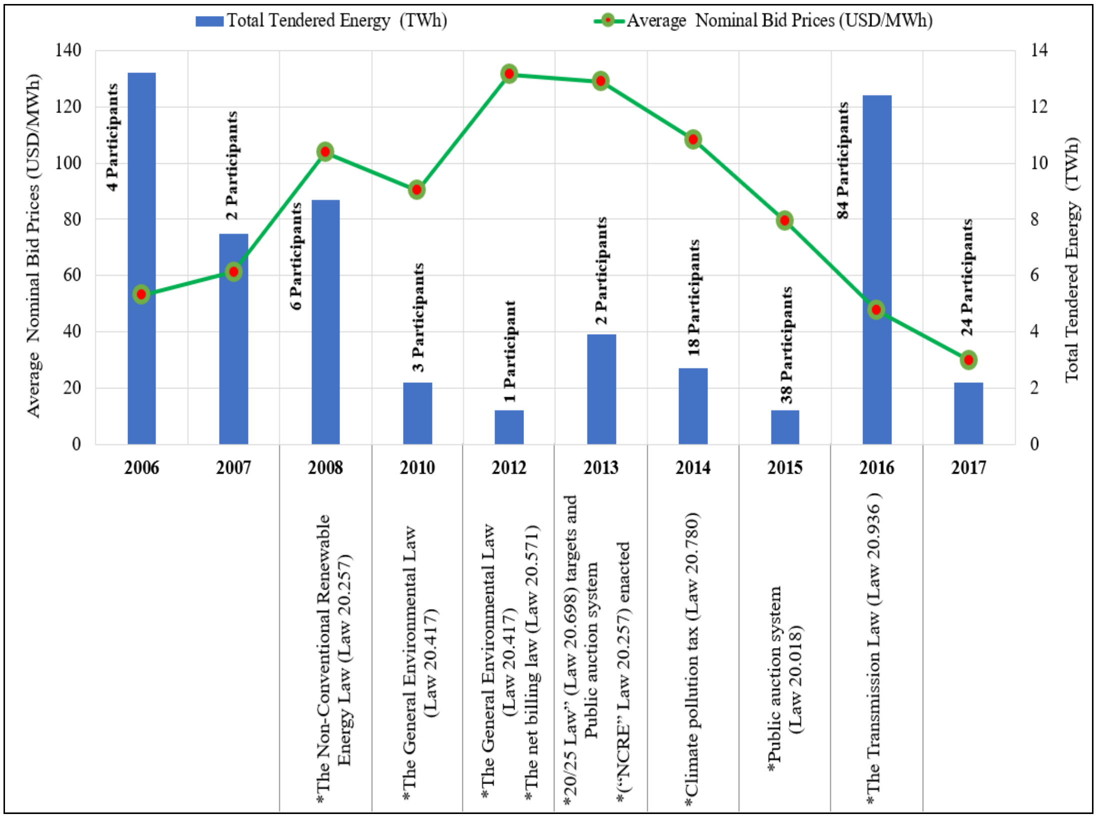


Figure 3- 6:The relation between the volume of tender, resulting in electricity price, and participants, in recent power auctions in Chile (Source: The figure was reconstructed based on References (Comisión Nacional de Energía, 2016; IEA, 2018)

Besides the national conditions, the possible reasons behind the bidding price reduction could be efficiently enacted laws, worldwide technological developments on renewables, and more auction participants due to competitive installation costs of renewables, or the combination of some of these factors.

In this analysis, the aim is to understand the possible factors that stimulate renewable energy adoption in Chile. Besides the effect of national conditions such as understanding the real potential of renewable energies in the country and implementing suitable laws and policies to promote them, it must be noted that the effects of global factors are inseparable from these analyses. Rising transition from fossil fuels to renewable energy, globally technological advancements on renewables in terms of generation and storage, more reasonable and efficient production of renewables, rapidly falling and competitive costs of renewables, and hybridization potential of renewables with other technologies are also possible reasons for increasing renewable energy capacity in Chile especially for solar and wind.

In Figure 3-7, global levelized costs of electricity (LCOE) of utility-scale renewable power generation technologies between 2010–2018 are presented for PV, CSP, wind, hydro, geothermal and bioenergy technologies. PV and CSP technologies showed a significant reduction in the last eight years due to development of technology as shown in the figure. The LCOE of PV projects reduced from 0.37 to 0.09 USD/kWh, which showed 77% decline between 2010 and 2018. The decrease between 2010 and 2018 in the global weighted-average LCOE of CSP is obtained from 0.34 to 0.19 USD/kWh with 46% reduction. The LCOE for offshore wind in 2018 was USD 0.127/kWh which is 20% lower than in 2010. The decline between 2010 and 2018 in the global weighted-average LCOE of onshore wind projects was 35%. Also, the LCOE in 2018 of new geothermal plants commissioned was 0.072 USD/kWh which is 1% lower than in 2017 when it was 14% lower than in 2017 value for bioenergy power plants. Finally, The increase between 2010 and 2018 in the global weighted-average LCOE of hydropower was from 0.04 to 0.05 USD/kWh, with 29% rise (IRENA, 2019).

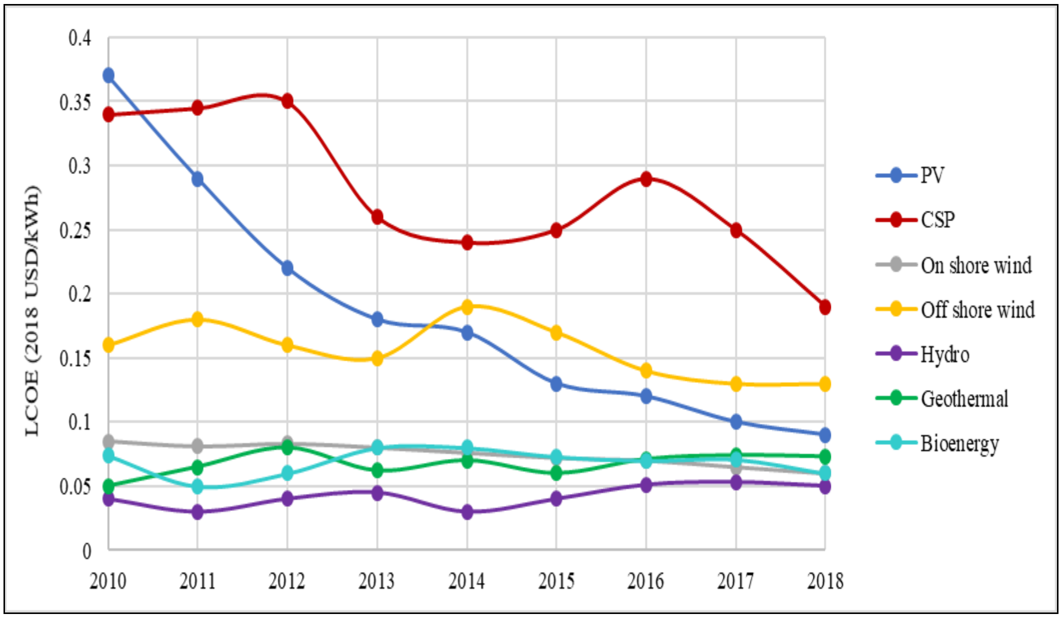


Figure 3- 7:Global LCOE of utility-scale renewable power generation technologies, 2010–2018. Source: The figure was reconstructed based on References (IRENA, 2019)

In conclusion, the reasons behind the development of renewable energy technologies can be the combination of successfully implemented laws and the mentioned global factors in the same period or individual impact of each of the mentioned factors.

3.3.3. Current policy assessment

In this section, the multi-criteria analysis of current energy policies was realized by using a weighted sum method. After the current energy policies (listed in Table 3-3) were classified based on three categories: legislative, monetary, and regulatory, the MCDA was conducted for each group. As mentioned in previous sections, assessment criteria were obtained from the literature review and their weights were obtained by Chilean energy experts via survey.

In Figure 3-8, the analysis results of legislative policies were presented. P22 (The significant target for RE capacity increase) had the best overall score with 0.851 when P16 (the electricity generated by hydropower projects under 20MW are eligible for quota obligation) followed the renewable energy target with 0.752 overall scores. In contrary, P23 (Auctions for public lands) got the lowest overall score which is 0.462. Besides overall score which is the sum of four criteria, individual scores for main criteria can be obtained from the figure.

Although some policies have the highest overall effectiveness score, they may have lower results within the criteria. P22 (the significant target for renewable energy capacity) and P21 (a mandatory energy efficiency label for firewood stoves and pellet heaters) had the highest score: 0.300 and 0.233, respectively for the criterion relevant to sustainability which includes the sub-criteria: having the potential to reduce emission, contribution to the low carbon economy, having a clear long-term vision, and contribution to the independence of energy supply. Besides, for efficiency criterion which considers easy to implement and control, requires less institutions to put into practice, requires less time to implement, and encourages local and global investors, P14 (technology-neutral auction system to complement the existing quota obligation) and P16 (the electricity generated by hydropower projects under 20 MW are eligible for quota obligation) were found the most efficient policies. It is interesting to note that, P8 (energy label for residential buildings) had the lowest results in efficiency criterion.

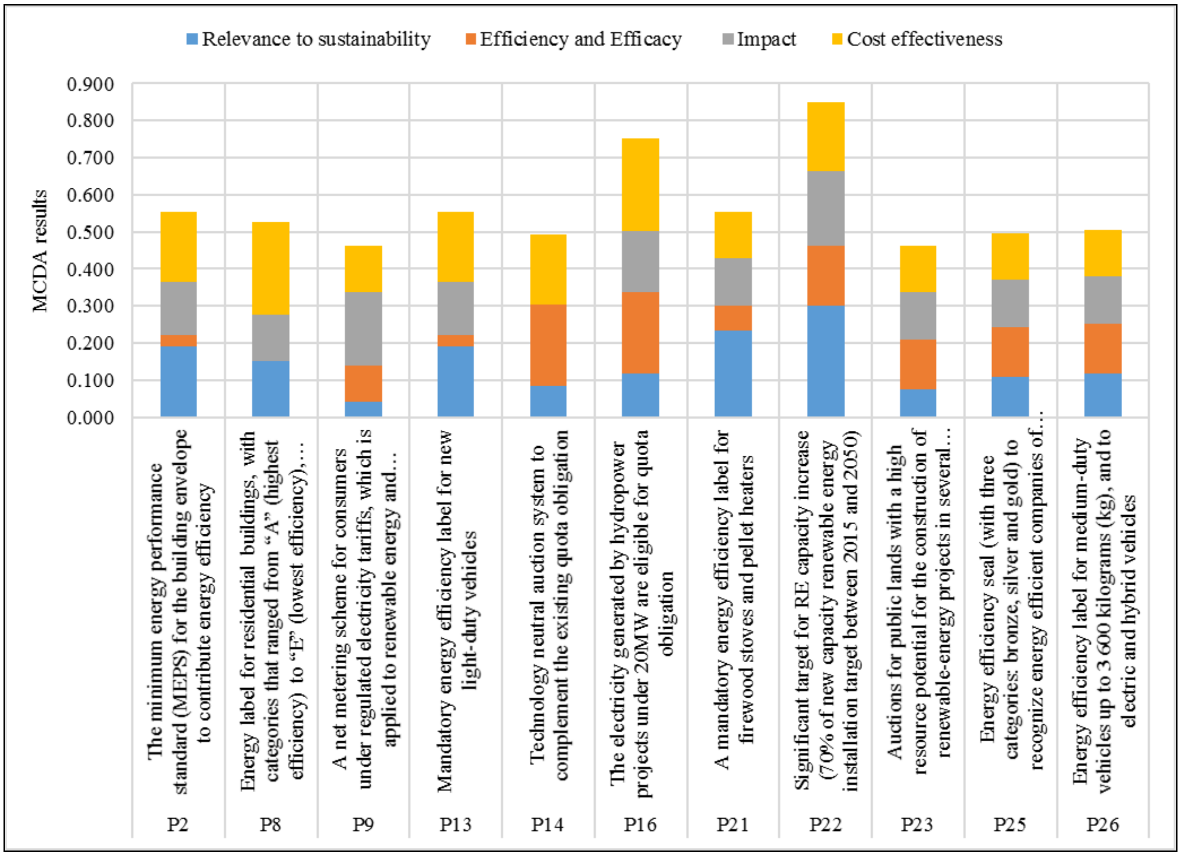


Figure 3- 8:The analysis results of legislative policies using MCDA

For the impact indicator which assesses the policies based on easiness to measure the impact, including quantitative targets, having an equal impact on the applied region, and having a long-lasting effect and benefits, most of the policies had similar results around 0.127 when P9 (net metering scheme) and P22 (renewable energy target) was obtained the best policies based on that criteria. Lastly, P8 (energy label for residential buildings) and P16 (the electricity generated by hydropower projects under 20MW are eligible for quota obligation) had the best score (0.250) for the cost-effectiveness criterion which includes cost-effectiveness for the government and the sufficient incentive for producers and investors.

Figure 3-9 presents the analysis results under the monetary category. As obtained from the analysis, and P20 (subsidies to encourage installing solar water heaters for residential) had the highest ranking (0.791), and P1 (partially subsidizing pre-feasibility and pre-investment studies for renewables) had the lowest overall score (0.238) in monetary class. P12 (Financial support for the establishment of solar energy research centre) was determined as the most efficient policy in terms of being easy to implement and control, requires less institutions to put into practice, requires less time to implement, and encourages local and global investors.

Additionally, for the impact indicator which evaluates the policies depending on easiness to measure the impact, including quantitative targets, having an equal impact on the applied region, and having a long-lasting effect and benefits, P15 (technology-specific support to provide a clear regulatory framework for geothermal exploration and development) had the lowest assessment score although it had better scores for sustainability and cost-effectiveness criteria. Finally, in terms of cost-effectiveness for the government and being a sufficient incentive for producer and investors, the majority of policies had similar scores due to including financial incentives and/or tax exemptions.

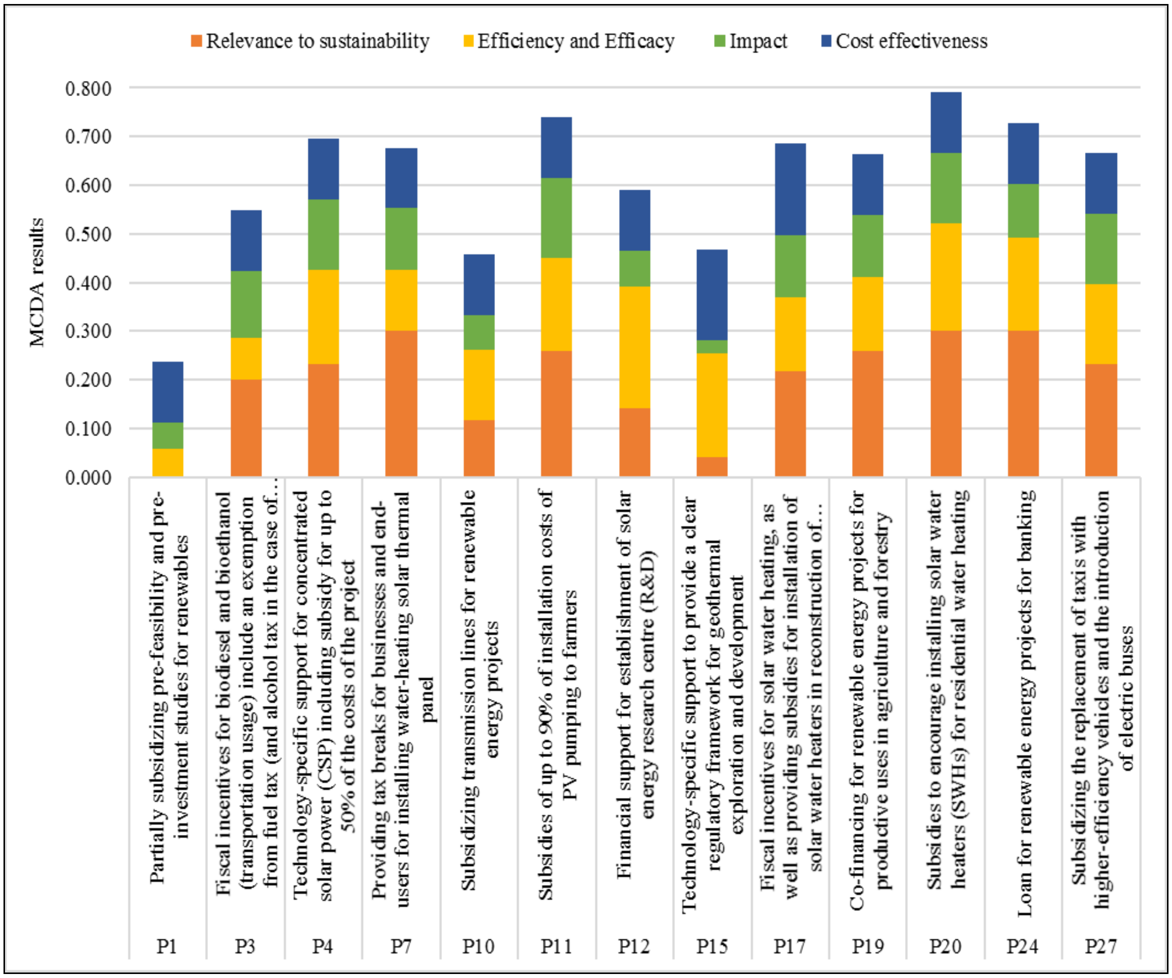


Figure 3- 9:The analysis results of MCDA for policies under the monetary category

After analyzing policies under the legislative and monetary category, four policies under regulatory classification were considered in the analysis. Figure 3-10 shows the results of policy analysis under the regulatory category. P6 (Regulations for solar water thermal including technical standards and certification systems) was found as the best regulatory policy with 0.686 overall score. Even though P6 was found a sustainable and cost-effective policy, it had low scores for efficiency and impact criteria.

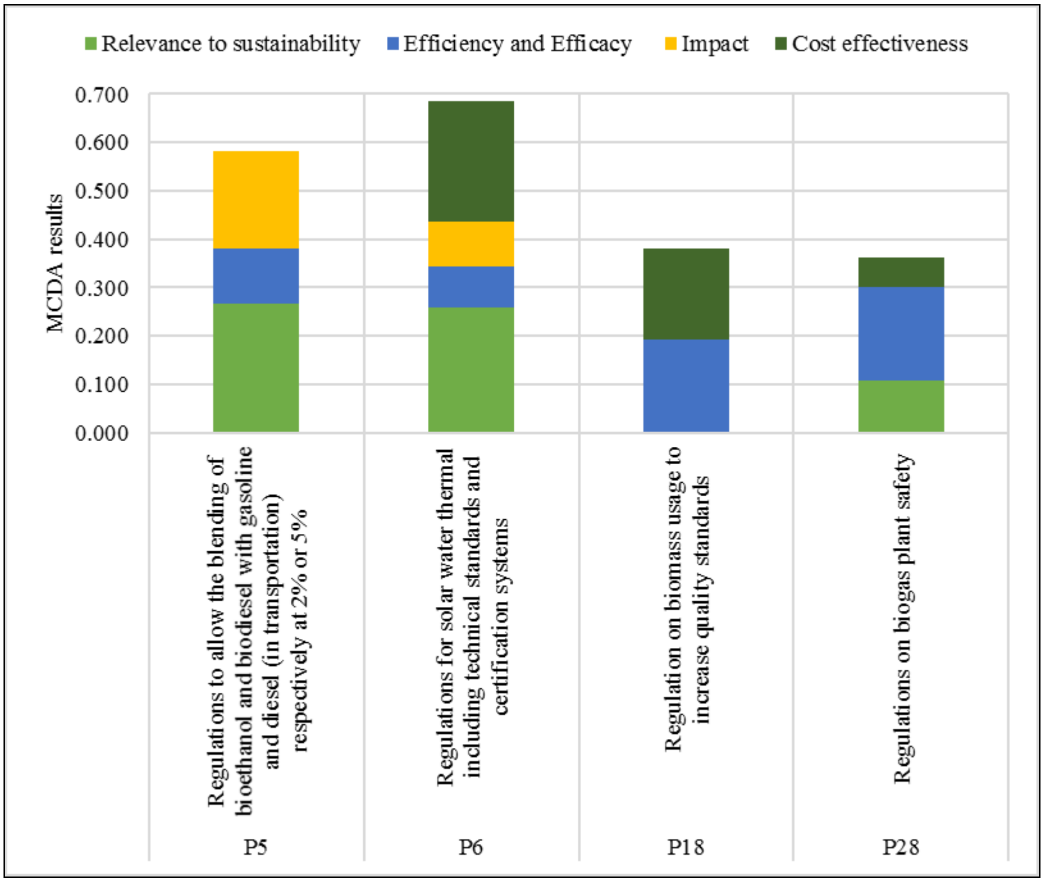


Figure 3- 10:The analysis results of MCDA for policies under the regulatory category

After that, P5 (regulations to allow the blending of bioethanol and biodiesel with gasoline and diesel (in transportation) respectively at 2% or 5%) had the second-best overall score although it was not found the cost-effective option. Additionally, although P18 (regulation on biomass usage to increase quality standards) was considered to be an efficient and cost-effective option, it was not found sustainable and having a significant impact. As a final point, P28 (regulations on biogas plant safety) was obtained a sustainable and efficient policy when it had low-cost effectiveness.

To conclude, policies with three different categories were analyzed based on the weighted sum method, which is a common method used for energy analysis. The ranking of each policy depends on criteria, criteria weights and policy assessment. In this research, when the overall score is considered, a legislative policy "P22 (the significant target for renewable energy capacity increase (70% of new capacity renewable energy installation target between 2015 and 2050)" which was enacted in 2015 was found the best policy between all policy alternatives. On the other hand, a monetary policy "P1 (partially subsidizing pre-feasibility and pre-investment studies for renewables)" had the lowest overall score in all policy categories.

Figure 3-11 shows the ranking of the best policies from each category based on the main criteria. For overall ranking, legislative policy P22 (the significant target for renewable energy capacity increase) had the best score, followed by monetary policy P20 (subsidies to encourage installing solar water heaters for residential water heating) and regulatory policy P6 (regulations for solar water thermal including technical standards and certification system). For three main criteria: relevance to sustainability, efficiency, and efficacy, and impact, legislative (P22: target for renewable energy) and monetary (P20: subsidies for residential water heating) policies had the best scores when regulatory one (P6: regulations for solar water thermal systems) was the best policy for cost-effectiveness.

Figure 3-12 presents the ranking of the worst policies from each category based on the main criteria. When the total score was considered, a monetary policy P1 (Partially subsidizing pre-feasibility and pre-investment studies for renewables) obtained the lowest results (0.237). Although P1 was found a cost-effective policy, its relevance to sustainability, efficiency and impact was not obtained effectively. After P1, a regulatory policy P28 (Regulations on biogas plant safety) had the lowest score in its category. For the impact indicator which evaluates the policies depending on easiness to measure the impact, including quantitative targets, having an equal impact on the applied region, and having a long-lasting effect and benefits, P28 had the lowest result even though it was found an efficient policy. Finally, P23 (Auctions for public lands with a high resource potential for the construction of renewable-energy projects in several locations) resulted in the lowest score in a legislative category with the low relevance to sustainability.

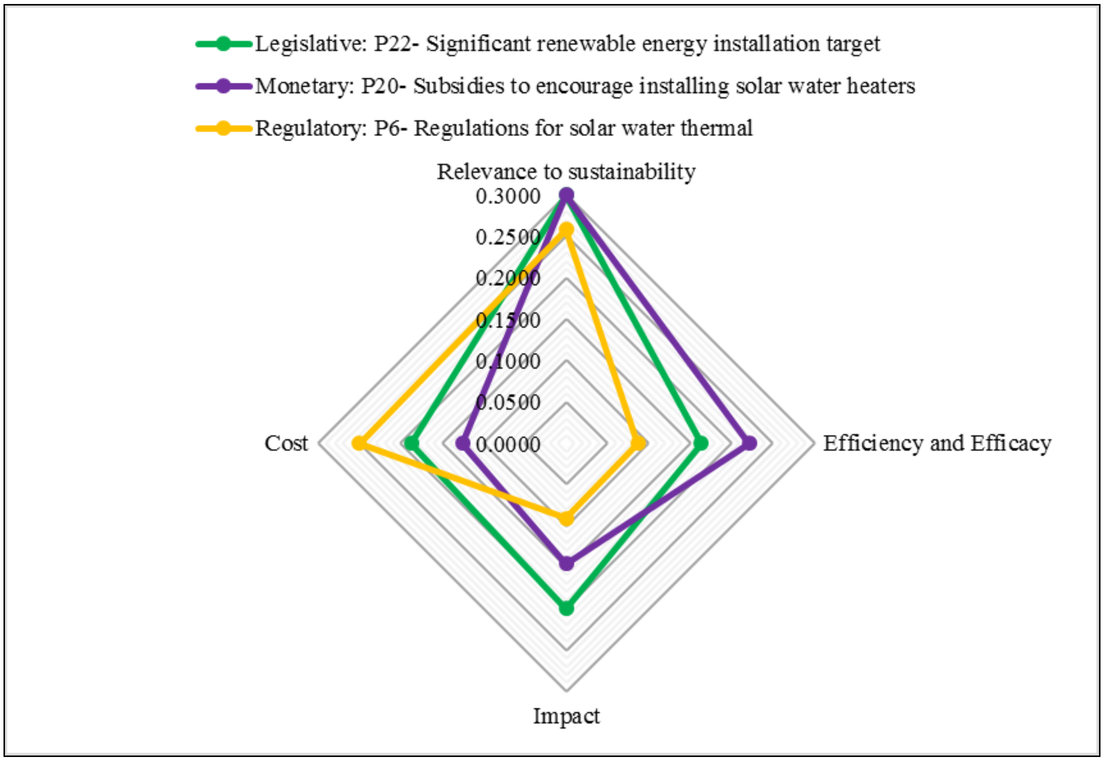


Figure 3- 11:The ranking of the policies with the highest scores from each category based on four main criteria, as obtained by MCDA

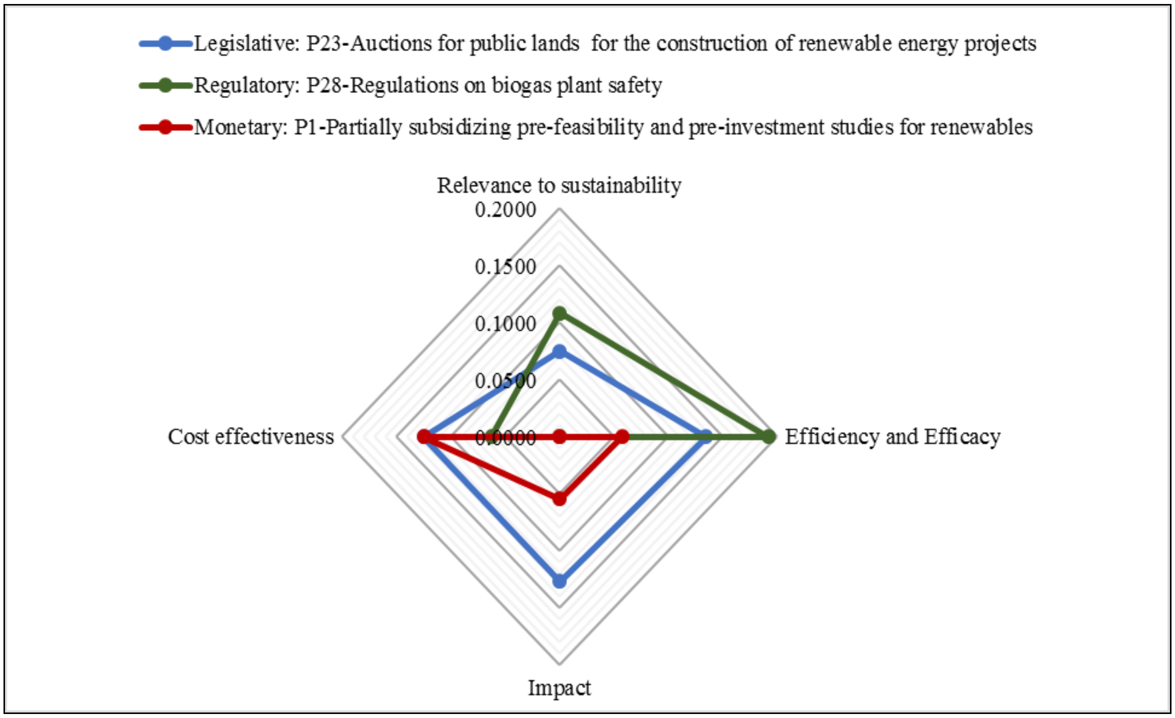


Figure 3- 12:The ranking of the policies with the lowest scores from each category based on four main criteria, as obtained by MCDA

As mentioned before, all these analyses are shaped by the conditions of the country, assessment criteria, and the importance of criteria for the country´s energy system and it may vary from one country to another.

3.4. Conclusion

This study has evaluated the renewable energy promotion in Chile by considering the global factors, energy policies, and it assessed the current policies by using multi-criteria decision analysis. This paper contributed to the literature by carrying out a systematic review to collocate renewable energy-related laws and policies in Chile, by obtaining policy assessment criteria from the literature, by weighing the criteria by consulting experts in the Chilean energy sector, and finally by conducting policy analysis bu using

MCDM, which has not been used so far to analyze energy policy in Chile in the literature. The aims of the research are to assess the renewable energy deployment in Chile by considering global factors and current energy policies, to develop a set of criteria to evaluate renewable energy policies and obtain criteria weights for policy assessment by expert opinions via survey and to apply the Multi-Criteria Decision Analysis (MCDA) method to understand the energy policy preference and developments in Chile based on the chosen criteria.

The results showed that solar and wind technology had more capacity increase than biomass and mini-hydro. Also, the capacity of solar PV and wind technologies showed significant increase after 2013. Renewable energy-related laws implemented between 2012 and 2017 could have the best impact on promoting solar energy technologies due to its positive PEIs. Policies to promote wind and mini-hydro technologies could be less effective than solar energy due to having lower PEIs. Energy policy to promote biomass also seems insufficient with its irregular PEIs for different years. Additionally, PV and CSP technologies showed a significant reduction in LCOE in the last eight years due to technological developments.

In the MCDA, policies with three different categories (legislative, monetary and regulatory) were studied based on the weighted sum method. The main results showed that when the overall score is considered, a legislative policy “the significant target for renewable energy capacity increase (70% of new capacity renewable energy installation target between 2015 and 2050)” was found the best policy between all policy alternatives according to experts´ assessment. Under the monetary policy, solar subsidies for the residential sector was obtained as the best option. Finally, regulation for solar thermal technology had as the highest score between regulatory policy alternatives. Otherwise, a monetary policy about subsidizing pre-feasibility and pre-investment studies for renewables had the lowest overall score between all alternative policies, which means the experts do not find pre-feasibility incentives useful to promote renewables anymore. As a conclusion, based on highest and lowest ranking obtained from the analysis, Chile needs to consider developing laws around the legislative frame and should be selective on monetary based policies when the technology and sectors are considered as in the example of incentives for solar technologies in the residential sector.

As mentioned before, all these analyses are shaped by the conditions of the country studied, the assessment criteria, and their importance for the country´s energy system. It may vary significantly from one country to another. Moreover, the methodology employed in this paper can bring very different results for other countries due to having a certain degree of subjectivity in the experts' views and various potential limitations in the application of the method. Further studies are planned to use this multi-criteria decision approach to future energy policies by considering energy experts´participation to generate sustainable scenarios for Chile.

3.5. Summary of the chapter

This chapter aims to assess the renewable energy deployment in Chile and analyze current renewable energy policies by using a multi-criteria decision method (MCDM) in which the policy assessment criteria are weighed by Chilean energy experts. The results show that the capacity of solar photovoltaic and wind power technologies showed a major growth after 2013 and the policy effectiveness index for solar and wind are obtained higher than biomass, mini-hydro and geothermal. Additionally, the multi-criteria analysis results showed that a legislative policy, which includes a target for renewable energy capacity, was considered as the most effective policy among all related alternatives. After understanding the current policy situation in Chile and expert opinions on energy policies, sustainable development goals analysis is conducted to be considered an extra scenario for energy model for Chile.

4. AN ANALYSIS OF ENERGY REQUIREMENT TO MEET THE SUSTAINABLE DEVELOPMENT GOALS

Abstract

The members of the United Nations came together in 2015 and agreed on seventeen sustainable development goals which include hundred and sixty-nine objectives related to sustainable development into the overall economic, environmental and social contexts of countries by 2030. In order to implement the goals, there is a need to analyse the energy requirement based on countries´ specific context. The objective of this paper is to assess the indicators of energy-related SDGs and calculate the energy requirement of each target when an intervention needs to meet the targets for 2030 in Chile. The key findings of the research are as follows: by considering growth rates obtained from available data, Chile meets sixteen targets out of twenty-four energy-related sustainable development targets without any interventions by 2030. Target 2.1, Target 5.b, Target 12.3, Target 13.1, and Target 17.6 require extra energy to be met by 2030. In order to meet SDGs in Chile, more energy is required by 2030 than the BAU scenario. Also, if Chile achieves its calculated energy intensity target instead of the global target, less energy will be demanded by 2030.

4.1. Introduction

In 2015, 193 members of the United Nations (UN) agreed on the sustainable development goals (SDGs) by targeting to eliminate discrimination and inequality, end poverty, and overcome climate change by 2030 (United Nations, 2019a). The Sustainable Development Goals include 17 goals and 169 objectives integrating matters related to sustainable development into the overall economic, environmental and social contexts of countries (Salvia et al., 2019).

After defining these targets, several studies were conducted based on SDGs since 2015 by developed and developing countries all around the world. The interconnections between energy and the SDGs was studied and twenty-four targets of SDGs which has direct links to energy were quantified to see their impact on energy demand (Santika et al., 2019). Also, Mccollum et al. worked on energy-related interactions between SDGs by assessing the relation of SDG 7 and other SDGs to demonstrate how energy policy implementation can affect other sustainable development targets (Mccollum et al., 2018).

Salvia et al. conducted research to identify the essential Sustainable Development Goals, local concerns and challenges of each region via a survey. In Latin America and the Caribbean, SDG 11, SDG 13 and SDG 4 were chosen as the most important goals to be investigated for the region, accordingly (Salvia et al., 2019). Costanza et al. examined alternative methods to link the SDGs to overall measures of sustainable wellbeing and suggested connecting them with a dynamics model which tracks stocks and flows, and make projections under different policy scenarios (Costanza et al., 2016). Sullivan et al. studied the connections between industrial ecology ethics, strategic management theory and achievement of the SDGs. The analysis presented that the integration of industrial ecology and business strategy is highly relevant for three of the SDGs (the efficient use of energy and resources, the pursuit of innovation, and mitigation of and adaptation to climate change (Sullivan et al., 2018).

Besides considering SDGs interactions, studies related to individual SDG targets and their implementations can be found in the literature. Herrera evaluated local authority challenges for SDG 6, which commits to guarantee sustainable water and sanitation for all. In the study, weaknesses in global monitoring efforts, creation of SDG to address them, local governance challenges facing SDG 6 and potential barriers to implementation were mentioned (Herrera, 2019). Moreover, the integrated multi-criteria decision-making analysis was realized to decide the most appropriate renewable energy source by addressing SDG 7. The most suitable renewable energy source was found as solar PV for Turkey to meet the SDG 7 (Büyüközkan et al., 2018). Srikanth worked on suggestions for the government of India to develop India's progress towards a low-carbon economy in parallel to the achieving SDG 7 target by recommending providing financial support to off-grid solar, wind and hybrid energy projects in the rural areas of India (Srikanth, 2018). Saladini et al. focused on three specific goals SDG2, SDG6, and SDG7, among the 17 SDGs. The purpose of this study is to introduce an observing tool ("water and food" oriented in the Mediterranean region) based on selected indicators designed on the SDG context (Saladini et al., 2018).

The contribution of renewable energy capacity increase to achieve SDGs for African countries also exist in the literature (Schwerhoff and Sy, 2017). Furthermore, the renewable energy potential of Vietnam and its challenges were studied to achieve the nationally determined contribution and the Sustainable Development Goals by highlighting the importance of renewable energy promotion and the international collaboration in Vietnam (Chan and Sopian, 2018). In addition to renewable energy, studies including the contribution of SDGs to energy efficiency also exist in the literature (Alawneh et al., 2018; Di Foggia, 2018; Puig et al., 2018).

Additionally, studies about particular subjects on renewable energy such as biomass also exist in the literature. Renzaho et al. investigated the biofuel production and its impact on food safety in developing countries. The findings showed that in the United States, European Union, Japan and Brazil, growing usage of food harvests to produce biofuels results with food price increase since 2000 while it is a potential threat to food and nutrition security in developing countries (Renzaho et al., 2017). Acheampong evaluated the biofuels potential to contribute to SDGs by presenting the development over the years. Although biofuels have a significant potential to support climate change mitigation, the adoption of large scale is considered as the main problem today. Nevertheless, it was also cited that third and fourth generation biofuel technologies are expected to be the future´s abundant, energy efficient and clean fuels to support the seventh SDG (Acheampong et al., 2017).

Some researches related to waste management can also be found in the literature to address SDGs. For instance, due to the lack of integrated planning frameworks, Fuldauer et al. developed an integrated approach for long-term waste management planning to meet SDGs in small island developing states. The results showed that waste prevention and material re-use strategies within islands could make a significant contribution to SDGs (Fuldauer et al., 2019). Dada and Mbohwa worked on municipal solid waste categorization to define the proportion of landfill wastes which can be used to produce energy to meet SDG 7 which includes sustainable and modern energy production (Dada and Mbohwa, 2017). Additionally, AlQattan et al. studied the linkage between waste and SDGs, including a comprehensive review of *waste to energy* technologies such as gasification, anaerobic digestion, and pyrolysis and their energy potential to support the worldwide ambition towards achieving SDG 7 and SDG 11 (AlQattan et al., 2018).

In addition to the studies mentioned above, some reviews about SDG scenario simulation tools can also be found in the literature. Allen et al. worked on a selection of appropriate modelling approaches to implement SDG targets. Between reviewed 80 models, eight models are observed to be of better applicability for national SDG planning (Allen et al., 2016). Moyer and Bohl worked on a model with three alternative policy scenarios "global technology, consumption change, and decentralized governance" for achieving SDG targets, in which the global technology pathway is found as the most successful at improving human development (Moyer and Bohl, 2018). Finally, the problems and barriers related to SDGs implementation (Gusmão Caiado et al., 2018) and also the connection between a group of socioeconomic and environmental factors linked to sustainable development goals (SDGs) are also studied in the literature.

In order to achieve sustainable development goals, each country should assess and analyse the energy requirement to meet each target according to its context. Although there are studies investigating the relationship of targets, not many studies analysing energy-related goals or calculating energy demand due to achieving these targets for developing countries. Moreover, although Chile has promised on Nationally Determined Contributions under the Paris Agreement, there are no studies in the literature neither about meeting SDGs for Chile nor energy demand analysis to reach SDGs in Chile. Therefore, there is a need to understand the energy requirement or savings to meet the SDGs for Chile in order to be considered in long term energy planning. This paper aims to evaluate the indicators of energy-related SDGs and calculate the energy requirement or savings for each target when an intervention is needed to meet the target for 2030 in Chile.

This article is organized as follows. Section 1 contains the review of the SDG related studies in the literature, the objective of the research, and contribution to the literature. Section 2 presents the methodological approach followed in the research, including a literature review and database search, analysis, case study application, and energy demand calculations for scenarios. Section 3 includes analysis results and discussion for Chile to achieve each target under relevant sustainable development goals. Finally, section 4 concludes the paper and includes suggestions for future research.

4.2. Methodology

The methodological approach of this research is presented in Figure 4-1. Three main steps are followed in the methodology as illustrated in the figure: 1) literature review and database search, 2) analysis, 3) case study application and 4) discussion and conclusion. The details of each phase are mentioned in the following sub-sections.

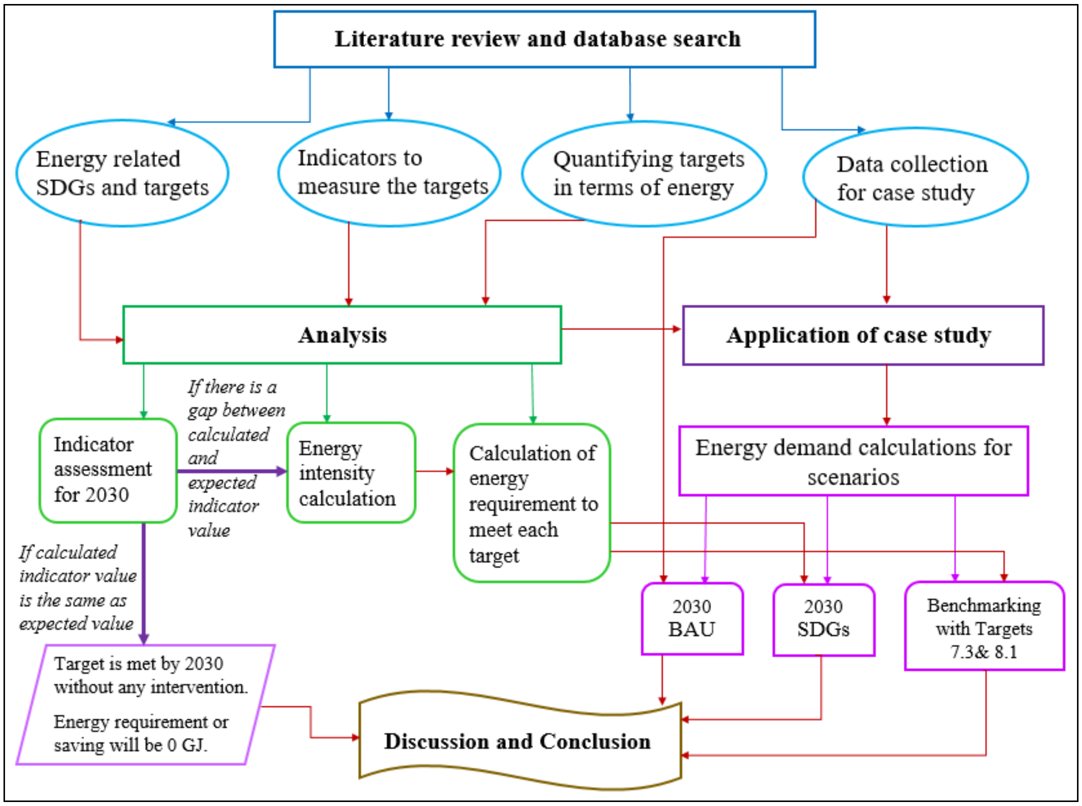


Figure 4- 1:The methodological approach of the research

4.2.1. Literature review and database search

In order to evaluate the energy requirement to meet Sustainable Development Goals, energy-related goals were obtained from the literature. Although several studies mentioned SDGs since 2015, few studies worked on the targets and also a specific study was found which worked on the targets with direct links to energy (Santika et al., 2019). Based on this study, twelve goals were found as having direct links to energy as listed in Table B1 in Appendix B.

Then, the indicators to measure the targets are determined from the literature review. The indicators are used to calculate the gap between the current situation and the targeted value for the year 2030 (Santika et al., 2019; The World Bank Group, 2017a; United Nations, 2019b). For instance, Goal 2 aims to end hunger and ensure food access for all. Therefore, the indicator "prevalence of undernourishment" is considered to assess Target 2.1. The indicators for all targets and related goals considered in this study are presented in Table B1 in Appendix B.

Finally, after determining energy-related goals and the indicator to measure the targets, quantification of targets to calculate the required energy to meet the goals by 2030 is obtained based on the studies in the literature. An approach with determining energy intensity for each indicator is taken into account to calculate the total required or saved energy to meet the target (Santika et al., 2019). Finally, global and local database searches are realized to collect information in order to apply this approach to a case study.

4.2.2. Analysis

The first step of the analysis is indicator assessment. Based on the available data for each indicator, the compound annual growth rate (CAGR) is calculated from the equation (4-1):

$$\boldsymbol{CAGR_{(calculated)} = \left(\frac{I\_value_{\_ending\ at\ T2}}{I\_value_{\_beginning\ at\ T1}}\right)^{\frac{1}{(T2-T1)}} - 1} \tag{4-1}$$

$\mathbf{I\_value_{\_beginning\ at\ T1}}$= The value for the indicator at year T1

$\mathrm{I\_value_{\_ending\ at\ T2}}$= The value for the indicator at year T2

T1: the year for the beginning value

T2: the year for ending value

After obtaining the growth rate from equation (4-1), the indicator value for 2030 is calculated as presented in equation (4-2):

$$I\_value_{\_BAU} = I\_value_{\_ending\ at\ T2} * \left(1 + CAGR_{(calculated)}\right)^{2030-T2} \tag{4-2}$$

I_value_{BAU}= The calculated value for the indicator at 2030 based on growth rate (BAU: Business as usual)

Finally, the gap between the calculated indicator value (business as usual) and the expected value to meet the target is calculated from the equation (4-3) as follows:

$$I\_value_{Gap} = I\_value_{2030} - I\_value_{BAU} \quad (4\text{-}3)$$

$I\_value_{\_Gap}$ = The gap between the calculated indicator value and expected value to meet the target

I_value_{2030} = The expected value for the indicator at 2030 to meet the target

If the calculated indicator value is the same as the expected value, it is assumed that the target is met by 2030 without any intervention. Thus, the energy requirement or saving will be 0 GJ. On the other hand, if there is a gap between calculated and expected indicator value for 2030, energy calculation is realized for these targets. Therefore, energy intensity (EI) calculation for each target is obtained from the literature. EI for each target can be a global value or depends on the country context.

Finally, the total required energy or energy savings to meet each target are calculated from the equation (4-4) by multiplying the energy intensity and indicator gap value as presented here:

$$E\_required\_total \text{ or } E\_total\_savings = EI * I\_value_{\_Gap} \quad (4\text{-}4)$$

4.2.3. Application of case study

Figure 4-2 shows the 2018 Global SDG Index scores and ranking for the first 50 countries. Sweden has the best SDG scores with 85 in the world and followed by Denmark, Finland and Germany. Although developed countries are seen at the top of the ranking list, it is interesting to see some developing countries between the top fifty countries such as

Moldova, Costa Rica, Chile and Cuba. In order to apply this method, Chile, having a score of 72.8 and it is 38th country in the SDG global ranking list (Sachs et al., 2018a), is considered as a case study to show how to calculate the required energy to meet SDGs. Chile is chosen due to being a developing country and having databases which are publicly available and easy to access. Global and country-wise databases were utilized to access and collect large data for the analysis. Finally, the indicator values and energy intensity to calculate the total required or saving energy were obtained for each target for Chile.

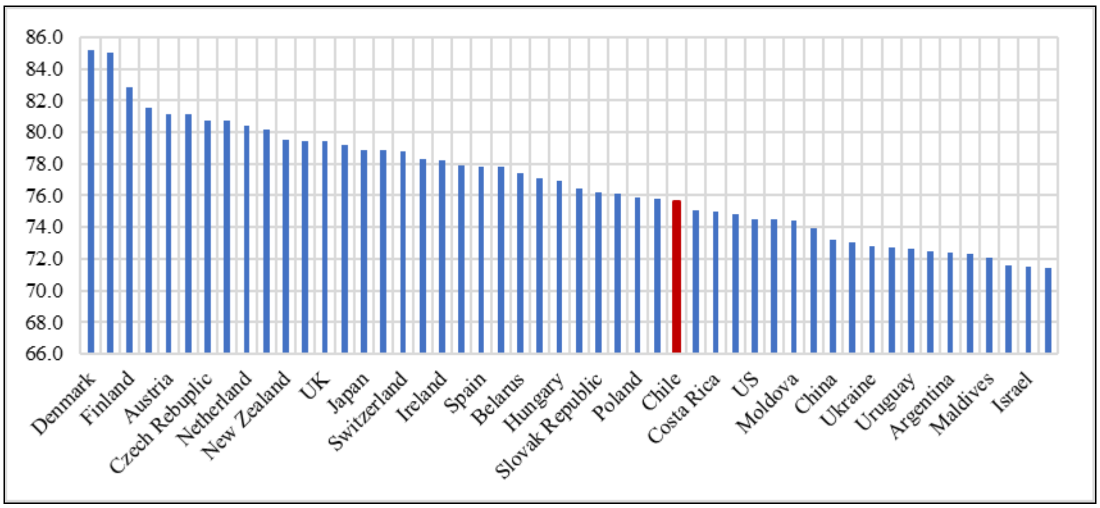


Figure 4- 2:The 2018 Global SDG Index scores and ranking (first 50 countries)

Source: The figure was constructed based on reference (Sachs et al., 2018b)

Therefore, analysis including indicator assessment, energy intensity (EI) calculation and the total required energy or energy savings to meet each target is realized for Chile. Then, two scenarios and a benchmarking are considered to compare the results to see the impact of SDGs implementation on Chilean energy demand by 2030. Firstly, the energy demand of 2030 for business as usual (BAU) scenario is calculated based on the available data from the national energy balance of Chile between 2008-2017. Then, energy demand for

SDGs scenario is calculated by taking into account the additional energy requirement from each target. Finally, benchmarking which considers Targets 7.3. and 8.1. is mentioned to crosscheck the total energy demand for 2030 and compared with two other scenarios. The detailed calculations are presented in the results and the scenarios were compared in the discussion section.

4.3. Results

This section presents the analysis results for each target under relevant sustainable development goals.

4.3.1. Goal 2_End hunger, achieve food security and nutrition

Target 2.1: By 2030, end hunger and ensure access by all people, in particular, the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round:

In order to assess Target 2.1, the indicator "*prevalence of undernourishment (% of the population)"* is considered (United Nations, 2019b). Based on the available data for Chile between 2000 and 2016, the prevalence of undernourishment is calculated by 2.41% of the population for 2030 as presented in Figure 4-3 which means 498,875.60 people will be undernourishment under the business as usual scenario (Instituto Nacional de Estadísticas, 2018). In order to meet the target which is ending hunger by 2030, all people must be nourished. Thus, the energy intensity is calculated based on equation (4-5) (Santika et al., 2019):

$$EI = D_f * EC_f / (Eon_{farm} + Eoff_{farm}) \quad (4\text{-}5)$$

Energy intensity can be calculated depending on different food content in countries nourishment plans. In this research, it is assumed based on potato due to the high amount of potato consumption in Chile. EI is calculated as 0.531 $GJ*cap^{-1}*year^{-1}$ (see Appendix B, Table B1). In conclusion, the energy requirement to meet the target (nourishing all people by 2030) is calculated by 265,057.83 GJ for Chile.

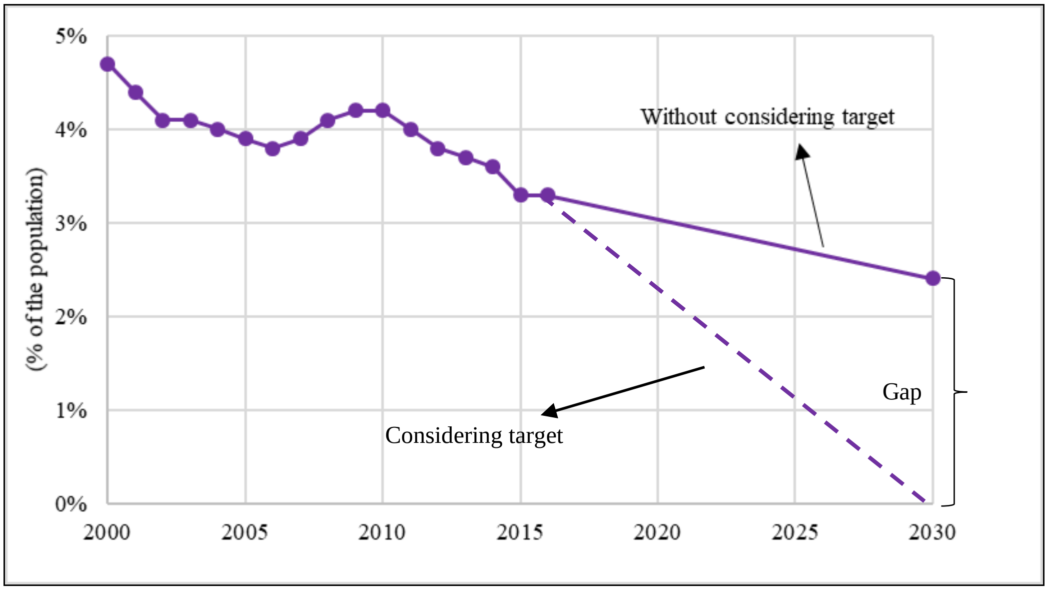


Figure 4- 3:Prevalence of undernourishment (% of the population) in Chile

Source: The figure was constructed based on reference (The World Bank Group, 2017a)

Target 2.3: By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment:

The recommended indicator to measure Target 2.3 is “cereal yield (kg per hectare)”. Data for cereal yield in Chile is accessed between 2009-2013 (The World Bank Group, 2017a). Also, the growth rate is calculated by 6.07% based on available data. The target aims to double the agricultural productivity compared to 2015, which means Chile should increase cereal yield from 7082 (kg per ha) to 14164 (kg per ha) by 2030. By considering the calculated growth rate, cereal yield in 2030 is calculated 14582 (kg/ha), which is more than planned value to double the agricultural production. Therefore, it is obtained that the target will be met in 2030 and no additional energy is needed to reach the target.

Target 2.4: By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality: Target 2.4 aims for sustainable farming which requires more efficient energy use in food production and therefore saves energy. The indicator *“proportion of agricultural area underproductive and sustainable agriculture”* is utilized to evaluate this target situation (United Nations, 2019b). A country which has sustainable agriculture targets will have 26.85% less energy per hectare than conventional agriculture (Alluvione et al., 2011). Based on the literature, the approximate energy saving will be 2.225 $GJ*ha^{-1}*year^{-1}$ when sustainable agriculture is considered (Fischer-Kowalski, 2008; Santika et al., 2019).

Based on the growth rate of 0.26% which is obtained between 2000 and 2016 for Chile, the total agricultural area for 2030 is calculated as 16,316,256.50 m^2 (The World Bank Group, 2017b). However, there is no target for Chile to make agriculture more sustainable. Therefore, the total energy saving to meet this target for Chile is assumed zero GJ.

4.3.2. Goal 3_Ensure healthy lives and promote well-being

Target 3.8: Achieve universal health coverage, including financial risk protection, access to quality essential health-care services and access to safe, effective, quality and affordable essential medicines and vaccines for all:

Target 3.8 is about ensuring healthy lives for all. The indicator “the number of people spending more than 10% of household consumption or income on out of pocket health care expenditure” is used to assess this target (United Nations, 2019b). Based on the growth rate 15.69% which is calculated from available data between 1997 and 2006 for Chile (The World Bank Group, 2017a), the target will be met without any interventions by 2030, which means surplus energy is not required.

4.3.3. Goal 4_Ensure inclusive and equitable quality education

In order to meet SDG 4 which is about education for all age groups, three targets were defined by considering pre-primary, primary, secondary, and tertiary educations. In order to measure the targets, gross enrolment ratio, which is the ratio of total enrolment, regardless of age, to the population of the age group that officially corresponds to the level of education, is considered (Trade Economics, 2018).

Target 4.1: By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes:

The first target in this goal is assessed by indicators of primary and secondary school gross enrolment ratios (The World Bank Group, 2017a). It is assumed that primary education is for children aged 7 to 12 and secondary education is for children aged 12 to 18 (Corsi-Bunker, 2011). Primary school enrolment (% gross) in Chile was informed at 99.8 % in 2016, according to the World Bank (The World Bank Group, 2017c). Thus, it is assumed that the target "primary school education for all" is already achieved before 2030. No additional energy is required to meet this target.

Moreover, secondary school enrolment in Chile (% gross) is 84.42% in 2000 and 99.66% in 2017 (The World Bank Group, 2017d). The growth rate calculated based on available data shows that the secondary school enrolment in Chile will reach 100% before 2030. Additional energy is not needed to reach the target, too.

Target 4.2: By 2030, ensure that all girls and boys have access to quality early childhood development, care and pre-primary education so that they are ready for primary education:

Pre-primary school enrolment is also considered in the SDGs with the Target 4.2. From the World Bank database, pre-primary school enrolment (% gross) data is obtained between 2013 and 2017 for Chile (The World Bank Group, 2017a). The growth rate is calculated as 2.15% with available data, which means the target for 100% pre-primary school enrolment will be met in 2030 in Chile. There is no surplus energy requirement to meet the target.

Target 4.3: By 2030, ensure equal access for all women and men to affordable and quality technical, vocational and tertiary education, including university:

Target 4.3, which is about tertiary education for all, is measured with the indicator *"school enrolment in tertiary education (% gross)"*. In Chile, the values for this indicator are obtained 36.22% in 2000 and 91.47% in 2017 (The World Bank Group, 2017a). Therefore, CAGR between 2000 and 2017 is calculated with equation (1) and found 5.60%. This growth rate shows that the target will be met before 2030 and the total energy requirement to reach the target is zero.

4.3.4. Goal 5_Achieve gender equality and empower all women

Target 5.b: Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women:

The indicator "proportion of individuals who own a mobile telephone" is proposed to measure the Target 5.b. which points achieving gender equality in technology usage (United Nations, 2019b). In 2016, 73.9% of the population had a mobile phone and also in 2020, 75.10% of the population is expected to have a mobile phone in Chile (eMarketer, 2016). In order to calculate 2030 value for this indicator, the growth rate is obtained as 1.18%, which resulted that 5,130,570.70 people (25% of the population) is estimated to be without a mobile phone in 2030 as presented in Figure 4-4.

The energy intensity requirement for a mobile phone is obtained 0.00519 $GJ*cap^{-1}*year^{-1}$ (see Appendix B, Table B1) (Carroll and Heiser, 2010; Santika et al., 2019). Therefore, the total energy requirement is calculated as 26,627.66 GJ to meet the target in Chile which is about enhancing the use of the mobile phone for all.

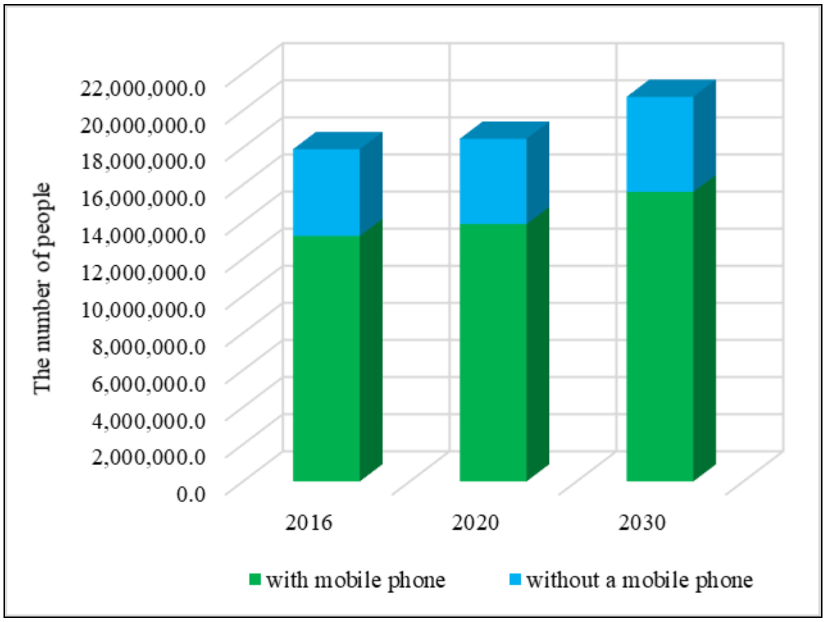


Figure 4- 4:The number of people with and without a mobile phone in Chile

Source: The figure was constructed based on reference (eMarketer, 2016)

4.3.5. Goal 6_Ensure availability and sustainable water management

Target 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all:

Availability of safe drinking water for all is another important target related to energy between SDGs. This target is assessed with the indicator *"proportion of the population using safely managed drinking water services"* (United Nations, 2019b). The improved water source mentioned in the target means being accessible on premises, available when needed and free from faecal and priority chemical contamination including piped water, boreholes or tube wells, protected dug wells, protected spring and packaged or delivered water (The World Bank Group, 2017a). For Chile, proportions of the population using safely managed drinking water is available between the years 2000 and 2015, which are

91.57% and 98.15%, respectively (The World Bank Group, 2017a). The growth rate is calculated 1.48% based on available data and it shows that if the growth in accessing safe water continues, as usual, all population will reach safe drinking water by 2030 and total energy requirement to reach the target is zero.

Target 6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally:

Another target under Goal 6 emphasizes the importance of quality water access. Target 6.3. is proposed to be measured with indicator “proportion of wastewater safely treated” (United Nations, 2019b). Data to measure this target for Chile is obtained between 2000 and 2015 from the database. The proportion of wastewater safely treated is increased significantly between these years as follows: 20.90% and 99.93%, accordingly (OECD data, 2019). The calculated growth rate shows that the target “100% wastewater treatment” is met before 2030 for this target in Chile. The total energy requirement to meet this target is zero.

4.3.6. Goal 7_Ensure access to affordable, reliable, sustainable energy

Target 7.1: By 2030, ensure universal access to affordable, reliable and modern energy services:

In order to evaluate this target, the *proportion of the population with access to electricity*, and the *proportion of the population with primary reliance on clean fuels and technolog*y indicators are utilized (United Nations, 2019b).

The first indicator for Target 7.1 “100 % electricity access” is already met in Chile by 2016 (The World Bank Group, 2017a). Access to clean fuels and technologies for cooking is another indicator for this target. The proportion of the population which accesses clean technologies for cooking is the indicator for this target. Data for Chile is available between 2000 and 2013, which shows that the ratio increased from 86.10% 91.67% in thirteen years (The World Bank Group, 2017a). Finally, the calculated growth rate (0.48%) shows that 100% of the population will access clean cooking technologies in 2030 without any intervention. Additional energy is not needed to reach the target.

Target 7.2: By 2030, increase substantially the share of renewable energy in the global energy mix:

Global electricity generation from renewable energy increased between the years 2015 and 2018, reaching almost 26.5%. The renewable electricity production in Chile also showed an increasing trend, which was increased from 15% to 19,92% from 2015 to 2018, respectively (Comisión Nacional de Energía (CNE), n.d.; IRENA et al., 2018; Renewable Energy Policy Network for the 21st Century (REN 21), 2018). The share of renewable energy is related to energy. However, the target does not affect the final energy consumption. Therefore, energy requirement or saving is not considered to calculate for this target.

Target 7.3: By 2030, double the global rate of improvement in energy efficiency:

This target which is measured with indicator *"energy intensity measured in terms of primary energy and GDP"* aims to double the global rate of improvement in energy efficiency based on 2010 (United Nations, 2019b). The global rate of improvement in energy efficiency is expected at 2.6% by 2030 (The World Bank, 2017). By considering this rate of improvement, the global energy intensity is calculated as 3.422 MJ/$2011 PPP GDP by 2030.

The energy intensity level of primary energy (MJ/2011 PPP GDP) for Chile is 3.777 (MJ/2011 PPP GDP) in 2015 based on accessible data for Chile (The World Bank Group, 2017a). When energy intensity for 2030 is calculated based on the growth rate, it is obtained 3.058 MJ/2011 PPP GDP for Chile, which is better than the global targeted value in 2030. Therefore, the target will be met before 2030 as presented in Figure 4-5.

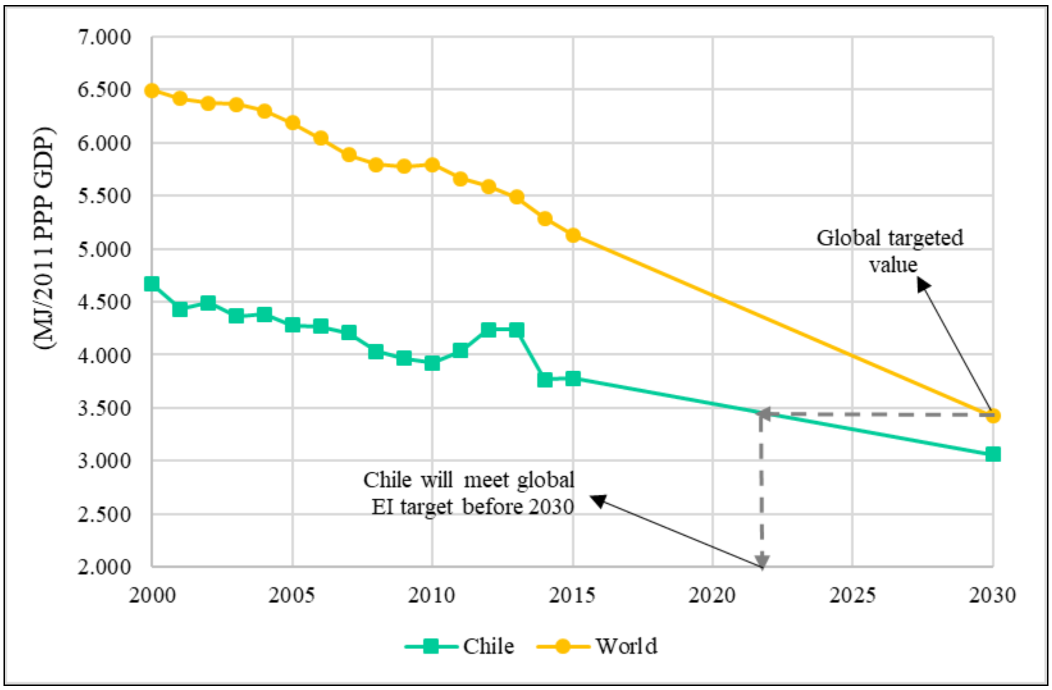


Figure 4- 5:The energy intensity (EI) level of primary energy (MJ/2011 PPP GDP) Source: The figure was constructed based on reference (The World Bank, 2017; The World Bank Group, 2017a)

4.3.7. Goal 8_Promote sustained, sustainable economic growth

Target 8.1: Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries:

Target 8.1. is assessed with the indicator *"annual growth rate of real GDP per capita"* (United Nations, 2019b). GDP PPP per capita between 2000 and 2017 is available in the database for Chile (The World Bank Group, 2018) and the growth rate is calculated as 2.80%. Thus, the calculated GDP per capita for 2030 is 32,592.96$ 2011 PPP/cap. The target aims that energy intensity in 2030 will be 3.422 MJ/2011 PPP GDP for Chile, which is also a global target (The World Bank Group, 2017a). Finally, the calculated total primary energy supply in 2030 for Chile has obtained 2,312,671,558.63 GJ. From Chilean National energy balances, the conversion ratio for energy supply to demand is obtained 70% (Comision Nacional de Energia, 2019). Therefore, based on Target 8.1, total energy demand is calculated as 1,618,870,091.04 GJ for 2030. This target is a reference point, which shows the expected energy supply and demand in 2030 and it can be used as a benchmark to check all targets energy requirement. In this study, the energy value obtained from this target is compared to BAU and SDG 2030 scenarios in the discussion section.

4.3.8. Goal 9_Build resilient infrastructure

Target 9.1: Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all:

Rural Access Index (RAI) (Eqbali et al., 2017), which is the share of rural people who live within 2 kilometers of the nearest all-season road is utilized to evaluate Target 9.1. For Chile, RAI (% of rural population) was obtained for 2002 and 2004, which are 59% and 76%, respectively (Fay and Morrison, 2005; The World Bank, 2004). With these available data, the growth rate is calculated 12.63% and it shows the target "100% of the rural population access to roads" will be met by 2030. The total energy requirement to meet this target is zero.

Target 9.c: Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in the least developed countries by 2020:

The indicator *"proportion of the population covered by a mobile network, by technology"* is considered to measure the Target 9.c. (United Nations, 2019b). Mobile network coverage (% population) in Chile is 100% by 2012 (GSM Association, 2007). Therefore, the target for 100 % of the population covered by a mobile network in Chile is already met before 2030. Additional energy is not required to reach the target.

4.3.9. Goal 11_Make cities and human settlements safe, sustainable

Goal 11 is about ensuring sustainable cities to citizens and it has three important targets which aim reducing the population living in the slums, providing sustainable transport system to public, and collection of solid waste regularly in the cities.

Target 11.1: By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums:

In order to evaluate the target, *"proportion of the urban population living in slums, informal settlements or inadequate housing"* is utilized as an indicator (United Nations, 2019b). In 2005, 9% of the urban population and in 2007, 1% of the total population lives in slums in Chile (Brain et al., 2009; The World Bank Group, 2017e). The population living in slums during last years in Chile reduced significantly. Therefore, the target which is "none of the population lives in the slums by 2030" will be reached before 2030. Thus, no additional energy is needed to reach the target.

Target 11.2: By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons:

In order to assess Target 11.2, indicator *"proportion of the population that has convenient access to public transport"* is considered (United Nations, 2019b). The proportion of the population uses public transport in Chile was announced at 29.10% in 2012 with a 0.5% annual decrease between 2001 and 2012 (El Ministro de Transportes y Telecomunicaciones, 2015). By considering this negative growth rate, only 20.10% of the population is expected to use public transportation in 2030. In Chile, there is no target to encourage people to use public transportation in 2030. Therefore, energy contribution is not considered for this target.

Target 11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management:

The indicator *"proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities*" is proposed to measure Target 11.6 (United Nations, 2019b). When generation and collection of solid urban waste data are investigated for Chile, it is found that since 2000, all generated solid waste is collected from cities in Chile based on the available databases (OECD data, 2018; OECD iLibrary, 2018; UN data, 2018). Therefore, the target "100% urban waste collection" is met before 2030.

4.3.10. Goal 12_Ensure sustainable consumption and production

Target 12.3: By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses:

Indicator *"global food loss index"* is utilized to assess the target which aims to halve global food waste per capita (United Nations, 2019b). The energy intensity which is obtained from the literature as presented in equation (6) is a function of food losses (L_half), energy consumption for storing (EC_storing) and retailing (EC_retailing) (see Appendix B, Table B1) (Santika et al., 2019; Smil, 2008):

$$EI = (EC_{storing} + EC_{retailing}) * L\_half \qquad (6)$$

Food losses in Latin America are obtained approximately 220 kg/cap/year based on the literature (FAO, 2011). The targeted food loss will be 110 kg/cap/year. Therefore, the total energy requirement from halving food waste in Chile is calculated as 10,263,968.06 GJ.

Target 12.5: By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse:

Target 12.5. is another objective under Goal 12 and it is measured with the indicator *"national recycling rate, tons of material recycled"* (United Nations, 2019b). The net energy reduction potential of recycling is obtained from literature as 1.64 GJ/tonnes (Beigl and Salhofer, 2004; Cleary, 2009; Santika et al., 2019).

The recycling rate of total waste in Chile is obtained at 0.4% in 2009 and 1% in 2013 (OECD, 2015; United Nations, 2011). Based on available data, it is calculated that 56.95% of the total produced waste will be recycled in 2030. However, there is no target for the recycling ratio of produced wastes by 2030 in Chile. Therefore, energy saving by meeting this target is not considered.

4.3.11. Goal 13_Take urgent action to combat climate change

Target 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries:

In order to evaluate this target, *the number of deaths, missing persons and directly affected people attributed to disasters per 100,000 populations* is considered as an indicator.

This target is essential for Chile due to having active volcanos, biggest recorded earthquakes and potential tsunamis in history. The number of people displaced after the last three biggest earthquakes and tsunamis in Chile is obtained as follows: 1,500,000.00 people in 2010, 970,000.00 people in 2014, and 1,000,000.00 people in 2015 (Barrionuevo and Robbins, 2010; NRC and IDMC, 2015). By taking into account the latest disasters, the average number of people displaces is obtained approximately 1,156,666.67 people. Also, the average embodied final energy intensity to build a temporary, post-disaster container house is approximately 1.35 $GJ*cap^{-1}*year^{-1}$ (see Appendix B, Table B1) (Santika et al., 2019). Thus, the total required energy to replace affected people after the disaster in Chile is calculated by 1,565,045.18 GJ.

4.3.12. Goal 17_Strengthen sustainable development

Target 17.6: Enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge-sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism:

Fixed internet broadband subscriptions per 100 inhabitants is the indicator to measure Target 17.6 (United Nations, 2019b). Data for fixed broadband subscriptions in Chile is obtained between 2010 and 2017 (The World Bank Group, 2019). The growth rate is calculated by 7.96% between available years. Thus, 12,454,704.18 people are expected to be without subscription in 2030. The energy intensity to meet the target is obtained 0.284–0.347 GJ/customer from the literature (Santika et al., 2019). When the average energy intensity is considered, the total energy requirement to meet this target for Chile is calculated as 3,927,715.51 GJ.

Target 17.8: Fully operationalize the technology bank and science, technology and innovation capacity-building mechanism for least developed countries by 2017 and enhance the use of enabling technology, in particular information and communications technology:

For Target 17.8., the indicator *"proportion of individuals using the internet"* is considered to measure the current situation (United Nations, 2019b). Data for individuals using the internet in Chile is available between 2000 and 2017 (The World Bank Group, 2017a). The calculated growth rate (10.97%) shows that the proportion of individuals using the internet will reach 100% of the population until 2030. Thus, additional energy is not needed to reach the target**.**

4.4. Discussion

By considering growth rates obtained from available data for each indicator, Chile meets sixteen targets out of twenty-four energy-related sustainable development targets without requiring any interventions by 2030. However, Target 2.1, Target 5.b, Target 12.3, Target 13.1, and Target 17.6 require extra energy to achieve by 2030 as presented in Figure 4-6. Target 12.3. which is about halving food losses requires maximum energy although Target 5.b. which aims to enhance the use of enabling technology needs the lowest energy to be met by 2030. When all SDGs are considered to be met, the total additional energy requirement is calculated 16,048,414.24 GJ.

In some cases, there can be overlapping or double counting between targets. For instance, Target 2.1 which is about ending hunger and Target 12.3 halving per capita global food waste by 2030 are related targets. By halving the food loss for Target 12.3, Target 2.1: ending hunger can be achieved naturally. Therefore, the linkage of targets should also be considered. In this study, all targets´ contribution to energy demand is calculated individually because Target 12.3 requires much more energy than other targets. Chile is one of the countries with the highest earthquake potential in the world. In history, it can be found that Chile was affected by drought, floods, tsunamis, volcanic eruptions, forest fires, and earthquakes. Thus, Target 13.1 is a vital target for Chile. It is hard to estimate the number of people displaced after disasters. In the analysis, the average number of people affected by natural disasters is taken into account based on the latest disasters in Chile. Another approach to estimate the number of people displaced after disasters can change the energy calculation.

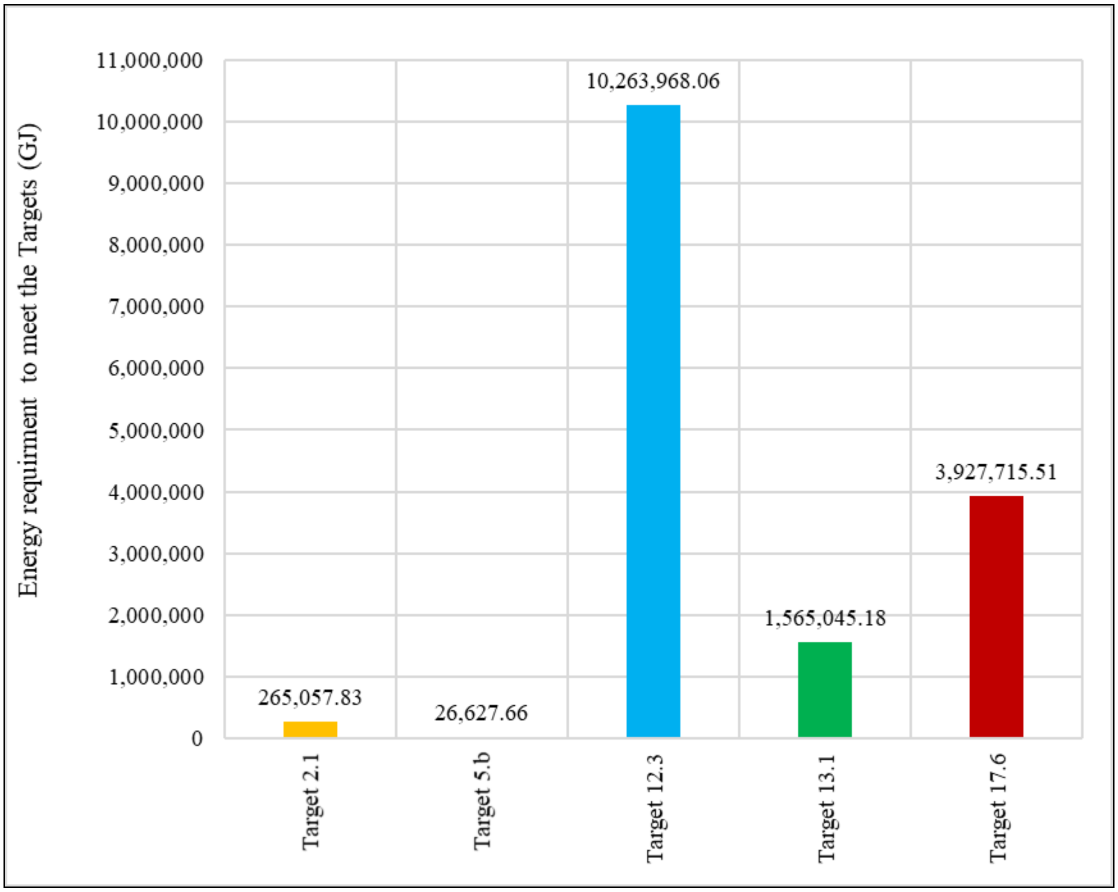


Figure 4- 6:The energy requirement to meet the five energy-related targets in Chile

Finally, the total energy demand for different scenarios and benchmarking for Chile are presented in Figure 4-7. Based on the available national energy balance reports for Chile between 2008 and 2015, the growth rate of energy demand is calculated 1.394% which is utilized to estimate energy demand for 2020, 2025 and 2030 BAU. Energy demand for BAU 2030 is calculated as 1,447.03 million GJ. Additionally, energy demand for 2030 considering SDGs (2030 SDGs) and benchmarking by considering Target 7.3 & 8.1 are illustrated in Figure 4-7. Due to additional energy requirement to meet SDGs, energy demand for 2030 SDGs was calculated as 1,463.08 million GJ which is more than business as usual scenario. Finally, in order to meet SDGs in Chile, more energy is required by 2030 than the BAU scenario.

In addition to BAU and SDGs scenarios, Target 7.3 and 8.1. are taken into account for benchmarking. When global energy intensity target (3.422 MJ/2011 PPP GDP) is considered total energy demand is calculated as 1,618.87 million GJ by 2030. It must be noted that if there is no target for a specific indicator in Chile, surplus energy is not considered. However, Target 2.4 and Target 12.5 may save energy if sustainable agriculture and recycling targets exist in Chile. On the other hand, Target 11.2 may require extra energy, if public transportation is improved to encourage people to use public transportation in 2030.

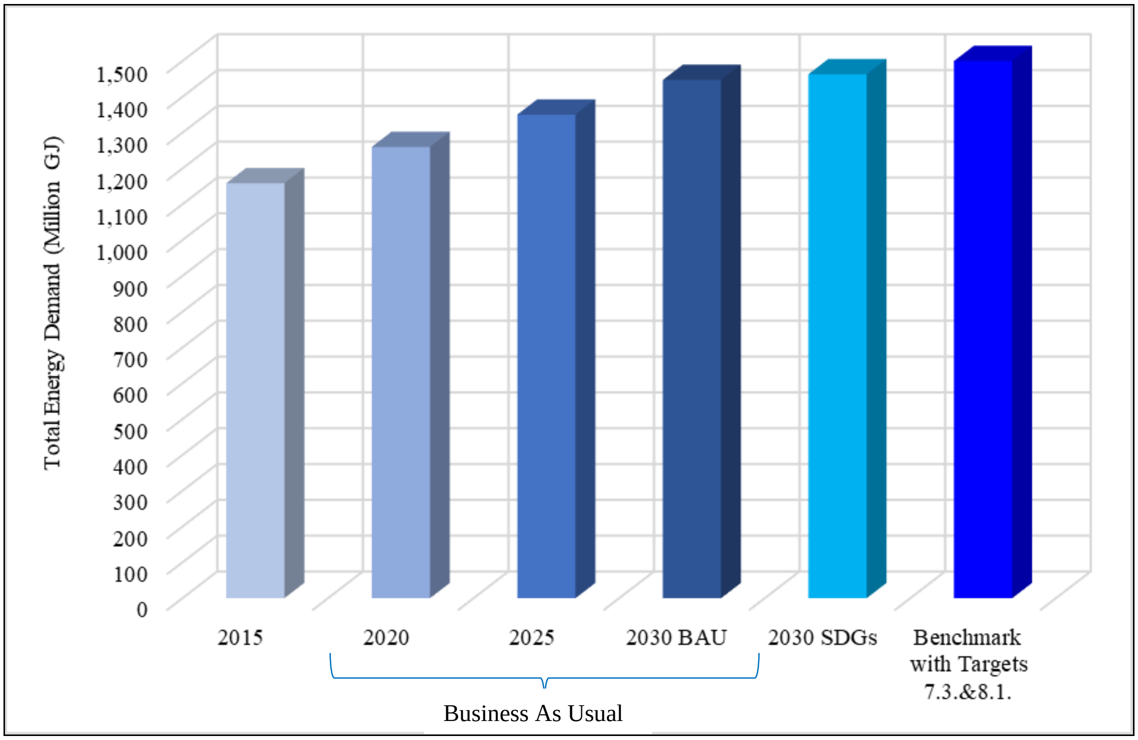


Figure 4- 7:Total energy demand and future projections for different scenarios in Chile (Source: The figure was constructed based on calculations in this study and reference (Comision Nacional de Energia, 2019)

The benchmarking calculations are done by considering Target 8.1. which is the global energy intensity target for 2030. On the other hand, energy intensity for Chile by 2030 is calculated 3.058 MJ/2011 PPP GDP, which is better than the global targeted value in 2030. Table 4-1 compares the global and calculated energy intensity, TPES and demand for Chile. When the calculated EI value is considered for benchmarking, the energy demand is obtained 1,446.67 million GJ. This energy value is closer to BAU 2030 result. It means that if Chile achieves its calculated energy intensity target instead of the global target, less energy will be demanded by 2030 when it is compared to other scenarios.

Table 4- 1:The comparison of global and calculated energy intensity, TPES and demand for Chile

	When global energy intensity target considered by Chile for 2030	When energy intensity calculated for Chile by 2030
EI (MJ/$ 2011 PPP)	3.422	3.058
TPES (Million GJ)	2,312.67	2,066.67
Demand (Million GJ)	1,618.87	1,446.67

4.5. Conclusion

This study has investigated the energy-related SDGs indicators and calculate the energy requirement or saving of each target when an intervention needs to meet the target for 2030 in Chile. The main findings of the research are: by considering growth rates obtained from available historical data, Chile meets sixteen targets without needing any interventions by 2030 between twenty-four energy-related sustainable development targets. As the analysis shows, Target 2.1, Target 5.b, Target 12.3, Target 13.1, and Target 17.6 require extra energy to be encountered by 2030.

Energy demand for BAU 2030 is calculated as 1,447.03 million GJ. When all SDGs are considered to be met by 2030, it is found that energy demand for 2030 SDGs was calculated as 1,463.08 million GJ due to additional energy requirement to meet SDGs. Thus, in order to meet SDGs in Chile, more energy is required by 2030 than the BAU scenario. When benchmarking is considered with Targets 7.3 and 8.1, total energy demand is calculated as 1,618.87 million GJ by 2030. In this study, if there is no target for a specific indicator in Chile, additional energy is not considered. However, Target 2.4 and

Target 12.5 may save energy or Target 11.2 may require more energy by 2030, which means that SDGs scenario could result in more or less energy than BAU by 2030.

This study includes some limitations due to assumptions. In order to achieve sustainable development objectives, each country should be assessed and analyse energy requirement to meet each target according to its conditions. These analyses are formed based on the conditions of the country studied, considered SDG assessment indicators, and energy requirement calculations based on literature review. It may vary significantly from one country to another. In some indicator assessment, data were available for only a few years and the growth rate is calculated based on existing data sets. The result can vary due to considering data sets for different years. Also, if there is no target for a specific indicator in Chile, surplus energy is not considered. However, Target 2.4 and Target 12.5 may save energy, in contrary, Target 11.2 may require extra energy in 2030. Also, the study only predicts energy demand and current energy policy for Chile is not consider for scenarios.

Further studies are planned to investigate the contribution of the calculated additional energy from SDGs to the sectors and to distribute this energy according to the fuel type for national energy balance in 2030. Finally, the discussion in this paper can support the provision of particular recommendations and insights for energy researchers working on implementing energy-related SDGs to the long-term sustainable energy planning of developing countries.

4.6. Summary of the chapter

Section 4 includes the research which assesses the indicators of energy-related SDGs and calculate the energy requirement of each target when an intervention needs to meet the targets for 2030 in Chile. The main findings of the research are as follows: by considering growth rates obtained from available data, Chile meets sixteen targets out of twenty-four energy-related sustainable development targets without any interventions by 2030. Target 2.1, Target 5.b, Target 12.3, Target 13.1, and Target 17.6 require extra energy to be met by 2030. The total additional energy requirement is calculated 16,048,414.24 GJ to meet these targets. Due to additional energy requirement to meet SDGs, energy demand for 2030 SDGs was calculated as 1,463.08 million GJ which is more than business as usual scenario. This research is also used as an input for the next chapter as an energy scenario for Chile. In the following section, energy and environmental model is developed by using LEAP to forecast energy demand, supply and emissions for Chile by 2030. Also, by considering studies in chapter 2, 3 and 4, scenarios are created by taking into account different policies motivated by current policy, NDC, SDGs.

5. COMPARISON OF ENERGY SCENARIO ALTERNATIVES FOR CHILE BY 2030: TOWARDS LOW-CARBON ENERGY TRANSITION

Abstract

The objective of paper is to generate energy and environmental model by using LEAP to forecast energy demand, supply and emissions for Chile by 2030 and create scenarios considering different policies motivated by current policy, national and international commitments of Chile. This paper contributes to the literature by developing 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 the transformation sector. Although emissions from transformation sector demonstrate significant reduction by 2030, the 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, PV solar, CSP solar and hydro power 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.

5.1. Introduction

Climate change is one of the worldwide challenges for humanity in recent years. Human activities in the energy sector are vital to contribute greenhouse gas (GHG) emissions, which are mostly produced by the fossil fuel combustion in, particularly, industry, transportation and electricity generation sectors (Chaichaloempreecha et al., 2019). Approximately 81% of global energy demand is met by fossil fuels including oil, coal, and gas (IEA, 2019). Growing demand, tentative fuel price, and the rising concern about climate change push countries to have long-term and sustainable energy planning. Therefore, many industrialized and developing countries have started to change their future energy plans towards de-carbonization by creating several alternatives scenarios to see the impact of national and international commitments on energy plans (Simsek et al., 2018a). 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 (Biblioteca del Congreso Nacional de Chile, 2012a; Congreso Nacional de Chile, 2009).

In the latest years, significant improvements in energy policy development can be observed (Simsek et al., 2018a). MAPS-Chile can be considered as the first project that developed projections and mitigation action plans to reduce greenhouse gas emissions in Chile (Gobierno de Chile, 2013, 2012; Ministerio del Medio Ambiente (Mitigation Action Plans and Scenarios), 2011). 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 (Ministerio de Energía, 2014). 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 (Comité Consultivo de Energía 2050, 2015). 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 (The Committee of Ministers for Sustainability and Climate Change, 2015). 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 (Ministerio de Energía, 2017). 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 (Ministerío de Energía, 2018). 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 (Simsek et al., 2018a).

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). Between these three grids, the National Electricity System includes thirteen regions and controls 99% of the total electricity supply of Chile (CNE, 2018a). 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 in the northern regions of Chile (Ministerio de Energía, 2015a; Ministerio de Energía División de Prospectiva y Política, 2018), also includes heavily energy-intensive activities. Chile mainly depends on imported fuels for energy supply with an approximate proportion of 71% in 2017. Oil is the principal 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 (Simsek et al., 2018a). Especially, the north of Chile has the best worldwide solar energy potential for energy generation, on account of dryness and clear sky (Escobar et al., 2015, 2014). 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 (IEA, 2018; Santana et al., 2014). 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 (Woodhouse and Meisen, 2011).

After the national and international commitments in Chile in the latest years, studies in the field of planning increased in the literature. There are some recently published studies related to electricity expansion planning for Chile (Gacitua et al., 2018; Quiroga et al., 2019; Ramirez Camargo et al., 2019; Rodríguez-Monroy et al., 2018; Rosende et al., 2019; Valdes et al., 2019). However, there are no published researches on demand forecasting, long-term sustainable energy planning, generating energy scenario alternatives for Chile including all sectors or studies analysing national/international commitments such as nationally determined contributions (NDCs) and sustainable development goals (SDGs). Motivated by this, this research contributes to the literature by generating an energy model for Chile and analyzing different scenarios which include energy strategies such as current policies, nationally determined contributions, sustainable development goals, and decarbonization. The purpose of this study is: 1) to create a model to forecast energy demand and supply for Chile considering different policies by 2030, 2) to analyse the energy-saving potential and decarbonization impact on energy planning for different scenarios in Chile such as current policy, NDCs and SDGs for Chile by 2030, and 3) to evaluate the determined scenarios if they meet their targets.

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.

5.2. Methodology

The methodological approach in this research is based on a literature review, scenario description, scenario quantification, results and comparison, as illustrated in Figure 5-1. Each stage is explained in additional detail within the following sections.

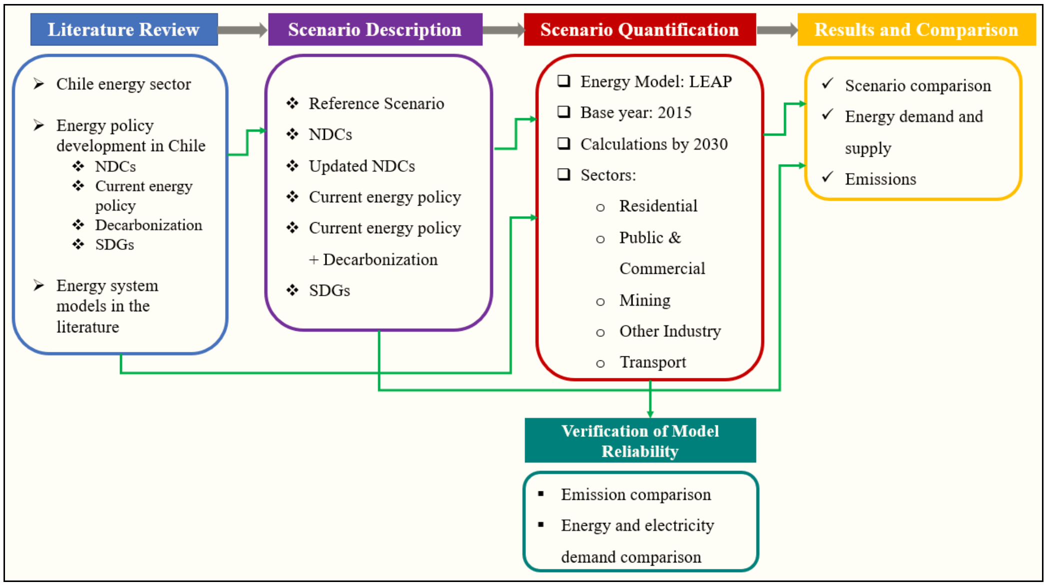


Figure 5- 1: Flowchart of the methodological approach

5.2.1. Literature review

The literature review is the initial step in the methodology, where information about the Chilean energy system, and energy policy development was collected and collated. Some of this information was presented in the introduction system. In order to understand energy sector in Chile and to create scenarios, current energy policy, renewable energy deployment, energy efficiency strategies, nationally determined contributions, sustainable development goals, decarbonization planning and related studies were also examined.

Additionally, 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 optimisation (BALMOREL, MESSAGE, RAMSES, etc.), and investment optimisation tools (MESSAGE, MARKAL/TIMES, RETScreen, etc) as categorized in References (Nyasulu, 2018; Ouedraogo, 2017).

In Table 5-1, some energy modelling studies obtained from literature in the last six 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) and developing countries (Greece, Iran, Turkey, Ethiopia, Bangladesh, Pakistan, Indonesia etc.) 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.

Table 5- 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*	(Giatrakos et al., 2009)
Resource planning integration	Energy	Iran	*LEAP*	(Amirnekooei et al., 2012)
Scenarios including uncertain aspects and technology options for clean energy usage	Energy	Greece	*LEAP*	(Roinioti et al., 2012)
Climate mitigation and global warming minimization potential	Electricity	Panama	*LEAP*	(McPherson and Karney, 2014)
Sustainable energy scenario options to meet the challenges of both energy security and means of climate change mitigation	Energy	Ethiopia	*LEAP*	(Senshaw, 2014)

Energy efficiency and CO_2 mitigation potential in the industry sector	Energy in Industry sector	Turkey	*LEAP*	(Ates, 2015)
The impact of renewable energy, energy conservation and efficient technologies	Electricity	Bangladesh	*LEAP*	(Rahman et al., 2015)
Renewables for energy security and carbon mitigation	Electricity	Indonesia and Thailand	*LEAP*	(Kumar, 2016)
Moderate energy access, accelerate energy access policies, renewable energies promotion and energy efficiency policies	Energy (Demand)	Africa	*LEAP*	(Ouedraogo, 2017)
Renewable Energy Potential for Thailand's NDC	Energy (Demand)	Thailand	*LEAP*	(Kusumadewi et al., 2017)
Policy analysis including renewable energy clean coal, energy efficiency and conservation	Electricity	Pakistan	*LEAP*	(Mirjat et al., 2018)
Reduction targets for greenhouse gas emissions for 2020 and 2050	Energy	Ireland	*TIMES*	(Gallachóir et al., 2007)
Climate and energy scenarios for 2050	Energy	Ireland	*TIMES*	(Chiodi, 2014)
Scenarios with different policies: CO_2 emission reduction constraint, renewable energy production targets etc.	Electricity	United Arab Emirates	*MARKAL*	(Mondal et al., 2014)
Low carbon development roadmap	Energy	Taiwan	*MARKAL*	(Tsai and Chang, 2015)
Emission reduction scenarios	Energy	UK	*MARKAL*	(Shmelev and Van Den Bergh, 2016)
Energy technology options under different scenarios	Electricity	India	*MESSAGE*	(Saradhi et al., 2009)
Energy mix and nuclear option in Malaysia taking into account the national energy policies	Energy (Demand)	Malaysia	*MESSAGE*	(Kumar et al., 2010)
Energy supply strategies by considering minimized the total system costs	Energy (Supply)	Syria	*MESSAGE*	(Hainoun et al., 2010)
New energy strategies introduced by the government including the nuclear power plant, hydropower and renewable energy	Electricity	Malaysia	*MESSAGE*	(Fairuz et al., 2013)

Scenarios with the lowest cost of generation and the lowest CO_2 emissions	Electricity	Indonesia	*Optimization Model*	(Purwanto et al., 2015)
Power system expansion planning under global and local emission mitigation policies	Electricity	Chile	*Optimization model*	(Quiroga et al., 2019)

LEAP is a software, developed by the Stockholm Environment Institute, Boston, to analyse energy demand and supply, energy policy, resource extraction, and accounting GHGs emissions (Heaps, 2012). In this study, LEAP was chosen as a modelling tool due to 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 (Nyasulu, 2018), and finally being free of charge for academics and PhD students.

5.2.2. Scenario description

The second 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 (fot detailed analysis of SDGs please check Section 4). Finally, six different scenarios were determined as follows and the comparison of scenarios can be seen in Table 5-2:

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 Nationally Determined Contributions (NDCs) of Chile, which was presented to the United Nations Framework Convention on Climate Change in 2015 (Simsek et al., 2018a; The Committee of Ministers for Sustainability and Climate Change, 2015).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 5-2.

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 (Gobierno de Chile, 2019). 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) (Ministerio de Energia, 2016; Ministerio de Energía, 2018). Based on these plans, 30% emission reduction, 30% energy demand reduction in residential sector, energy efficiency in major sectors, fossil fuels replacement with electricity, 60% electricity generation from renewable energy by 2035, fast improvement on T&D lines, and restriction on biomass usage in residential sector were considered.

Current Policy + Decarbonization Scenario: 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 (Coordinador Eléctrico Nacional, 2018; Ministerio de Energía, 2018; Ministry of Energy, 2015) 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 (See Section 4), Chile requires 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 C (Table C1).

Table 5- 2: The summary of scenario description

	Reference Scenario	***NDCs Scenario*** *(Gobierno de Chile, 2015)*	***New NDCs Scenario*** *(Gobierno de Chile, 2019)*	***Current Policy Scenario*** *(Ministerio de Energia, 2016; Ministerio de Energía, 2018)*	***Current Policy + Decarbonization Scenario*** *(Coordinador Eléctrico Nacional, 2018; Ministerio de Energia, 2016; Ministerio de Energía, 2018)*	***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.	45% emission reduction by 2030 compared to 2016.	30% emission reduction by 2030 compared to 2007.	30% emission reduction by 2030 compared to 2007.	30% emission reduction by 2030 compared to 2007.
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

	Reference Scenario	***NDCs Scenario*** *(Gobierno de Chile, 2015)*	***New NDCs Scenario*** *(Gobierno de Chile, 2019)*	***Current Policy Scenario*** *(Ministerio de Energia, 2016; Ministerio de Energía, 2018)*	***Current Policy + Decarbonization Scenario*** *(Coordinador Eléctrico Nacional, 2018; Ministerio de Energia, 2016; Ministerio de Energía, 2018)*	***SDGs Scenario***
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 (Generadores de Chile, 2017). 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 (Generadores de Chile, 2017). 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 (Generadores de Chile, 2017). 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 (Generadores de Chile, 2017). 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 (Generadores de Chile, 2017). 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 to 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 to 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 to 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 to 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 (Coordinador Eléctrico Nacional, 2018; Verastegui et al., 2019).	Real installed capacity and generation values were entered to 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 (Coordinador Eléctrico Nacional, 2018; Verastegui et al., 2019).

	Reference Scenario	***NDCs Scenario*** *(Gobierno de Chile, 2015)*	***New NDCs Scenario*** *(Gobierno de Chile, 2019)*	***Current Policy Scenario*** *(Ministerio de Energia, 2016; Ministerio de Energía, 2018)*	***Current Policy + Decarbonization Scenario*** *(Coordinador Eléctrico Nacional, 2018; Ministerio de Energia, 2016; Ministerio de Energía, 2018)*	***SDGs Scenario***
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.	EE is considered for all sectors. Biomass usage was restricted in the residential sector.	EE is considered for all sectors. Biomass usage was restricted in the residential and other industry sector.	EE is considered for all sectors. Biomass usage was restricted in the residential and other industry sector	EE is considered for all sectors. Biomass usage was restricted in the residential and other industry sector

5.2.3. 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 (IEA, 2018; OECD, 2018c). Thus, mining sector was analysed in the model separately from other industry sectors. The defined scenarios from the previous step were quantified and implemented to the developed energy model.

The equations considered in the model for energy demand, net energy consumption for transformation, carbon emissions from final energy consumption, and carbon emission are presented as follows (Heaps, 2012; Nyasulu, 2018; Ouedraogo, 2017).

Energy demand is a function of activity level and energy intensity for each sector, and it is calculated as Eq (5-1):

$$ED_{b,s,t} = TA_{b,s,t} * EI_{b,s,t} \tag{5-1}$$

ED: energy demand

TA: total activity

EI: energy intensity

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

Additionally, the net energy consumption for transformation is calculated as Eq (5-2):

$$ET_p = ETP_{sec,tec} * [\frac{1}{f_{p,sec,tec}} - 1] \quad (5\text{-}2)$$

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

ETP: product from the transformation process

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 (5-3):

$$CE_{p,s,t} = TA_{b,s,t} * EI_{b,s,t} * EF_{b,s,t} \quad (5\text{-}3)$$

CE: carbon emissions,

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

Finally, the emissions from energy transformation are calculated as shown in equation 5-4:

$$CET = ETP_{sec,tec} * \frac{1}{f_{p,sec,tec}} * EF_{p,sec,tec} \quad (5\text{-}4)$$

CET: the carbon emission

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

LEAP requires demographic and macroeconomic data for the modelling as shown in Figure 5-2 (Heaps, 2012). In this study, activity level and energy intensities are assumed as listed in Table 5-3. 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. Besides key assumptions such as demographics and macroeconomic data, LEAP requires historical energy demand and transformation data to forecast future values. Transformation analysis includes the supply of electricity generation processes, technologies and related data. LEAP allows generating several scenarios with the created model and compares the results based on energy and environmental outputs.

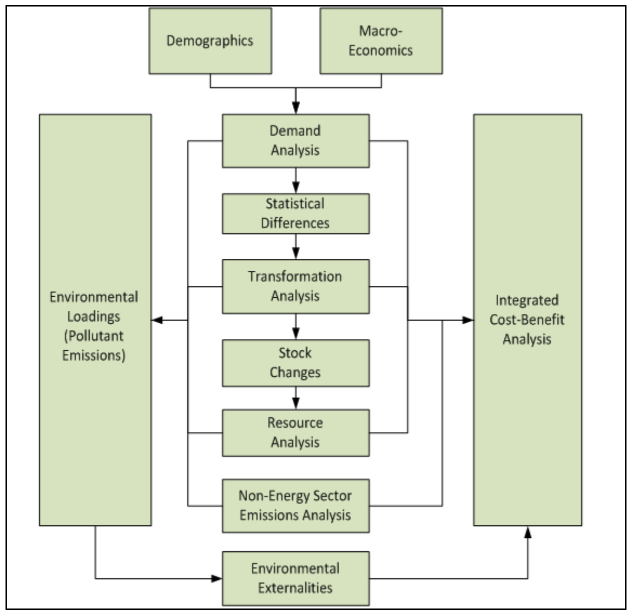


Figure 5- 2:The structure of LEAP calculations (Heaps, 2012)

Table 5- 3:Activity level and energy intensity assumptions

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

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 reports, and publicly available Chilean governments´ reports. For instance, national energy balances are reported annually in the website of National Energy Commission of Chile (Comisión Nacional de Energía (CNE), n.d.). Demographic data are obtained from National Statistics Institutes of Chile and World Bank Group (Instituto Nacional de Estadísticas, 2018; The World Bank Group, n.d.). Macroeconomic data are taken from international statistic websites, Chilean government report and ministries publicly available documents (Cantallopts, 2016; Ministerio de Agriculturas ODEPA, n.d.; Statista group, n.d.). Moreover, required data for transformation part of the model such as power plant installed capacities and historical generation are acquired from the reports and website of National Energy Commission of Chile (Comision Nacional de Energia Electrica, 2019). Technology and power plant information such as availability, efficiency are taken from published peer-reviewed articles, LEAP database, and international thesis (Gaete-Morales et al., 2019; Heaps, 2012; Şahin, 2014). Finally, emission impact data is taken from available database in LEAP model: Technology and Environmental Database (Heaps, 2012).

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.

5.3. Results and Discussion

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.

5.3.1. 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 5-4 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) (United Nations, 2018) 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. In contrary, LEAP values are obtained lower than UNFCCC values with 1.5-2.2% error margin for 2014 and 2015.

Table 5- 4:CO_2 emissions (without LULUCF / LUCF) values obtained from UNFCCC and LEAP results for base case (MMetric Tonnes CO_2)

Year	**UNFCCC values** (United Nations, 2018)	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 governments national energy balances as presented in Table 5-5. 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 (Comision Nacional de Energia, 2019; Ministerio de Energía División de Prospectiva y Política, 2018) with 0.23% and 0.27% error margin, accordingly.

Table 5- 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 (Ministerio de Energía División de Prospectiva y Política, 2018)	285,430	0.23%	-	-	-
2017	288,901 (Comision Nacional de Energia, 2019)	289,670	0.27%	-	-	-
2030	*350,000 (low)*-400,000 (high) (Ministerio de Energía, 2017)	344,760	-1.50%	*100,000 (low)*-115,000 (high) (Ministerio de Energía, 2017)	95,388	-4.61%

Also, 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 will vary between 350,000-400,000 Tcal (Ministerio de Energía, 2017). 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 (Ministerio de Energía, 2017). When low electricity demand projection of government is compared to the calculated value, LEAP results showed lower demand value for electricity with -4.61% error margin for 2030.

5.3.2. Comparison of scenarios

Figure 5-3 shows 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 20% energy saving target by 2025. Due to its major emission reduction target, the new NDC scenario should have at least 38.5% reduction in energy demand when it is compared to the reference scenario by 2030. Thus, New NDC policy shows the lowest demand for 2030 which is 887 million GJ when it is compared to other 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 current policy scenario and it was obtained approximately 997 million GJ by 2030. Finally, NDC scenario has 20% reduction target from total demand by 2025 when current policy scenarios have 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.

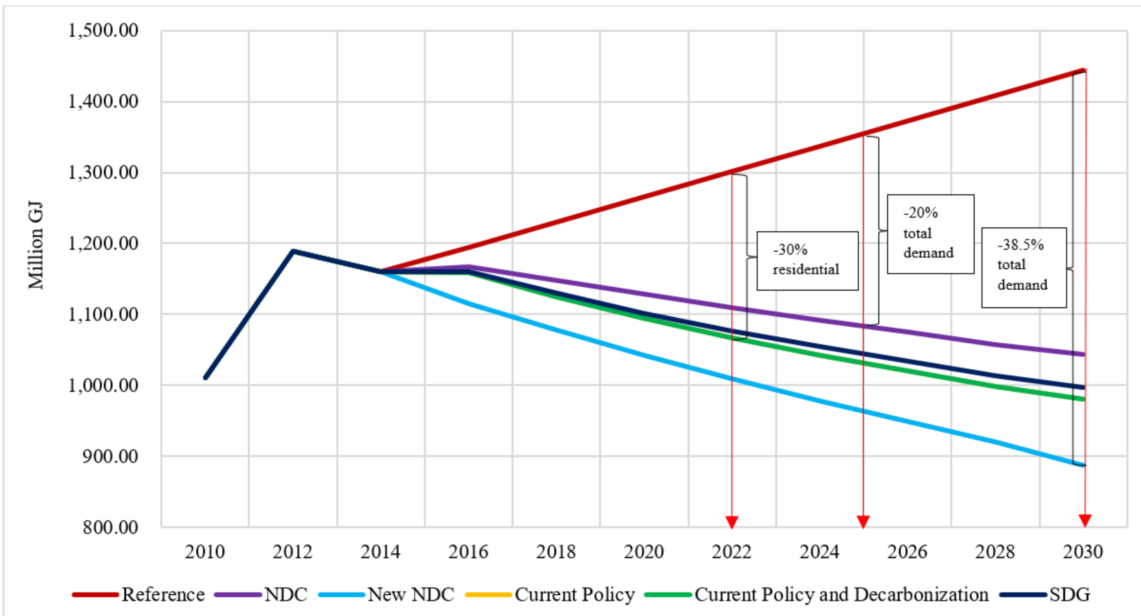


Figure 5- 3:Total energy demand projection for scenarios

Figure 5-4 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. Demand decline in residential sector at current policies can be seen clearly due to their specific efficiency targets when it 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, 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.

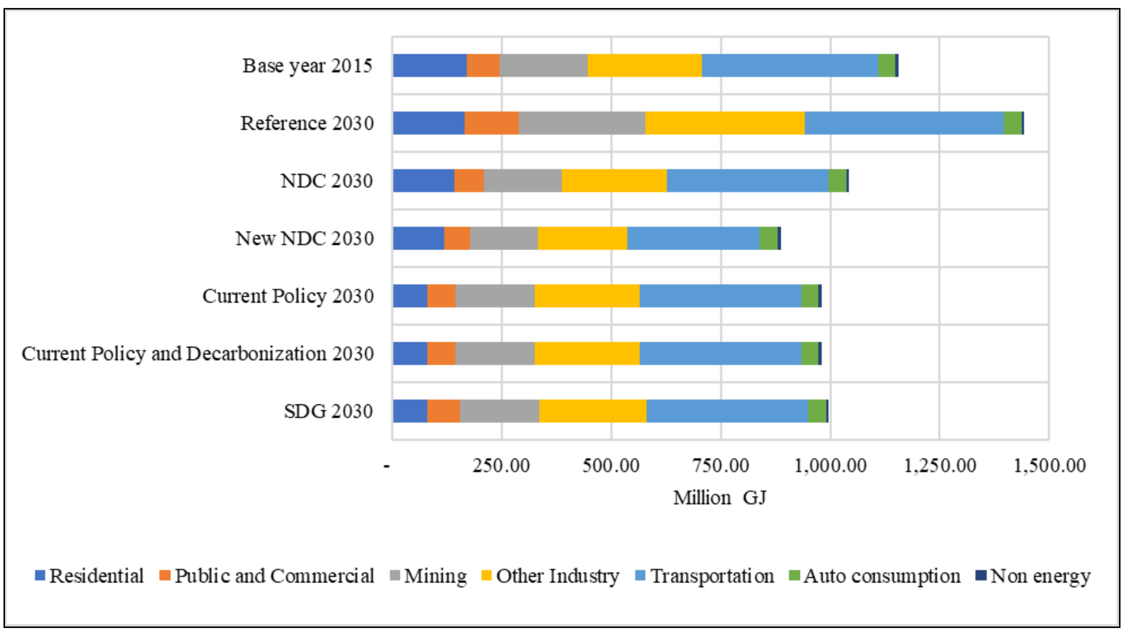


Figure 5- 4:Sectoral energy demand for each scenario at 2030

In Figure 5-5, CO_2 emission (Million Metric Tonnes CO_2 Equivalent) and CO_2 emission per GDP (Billion US$) graphs are illustrated. As summarized in Table 5-2, the new NDC scenario has 45% compared to 2016 and other scenarios have 30% emission reduction targets compared to 2007. After applying all strategies to each scenario, emissions are decided as a control mechanism to check if the scenario is meeting emission reduction or not. According to United Nations Framework Convention on Climate Change (UNFCCC) reports for Chile, CO_2 emission had the major share which was 74% in 2000 and 81% in 2016 (last reported year) between all greenhouse gas (GHG) emissions (United Nations, 2018). Due to its significant impact, CO_2 emissions are considered and compared in this study. The CO_2 emission (without land use, land-use change and forestry (LULUCF)) value for 2007 and 2016 in Chile were 62.46 and 87.44 million metric tonnes, accordingly. When CO_2 per GDP values are calculated, they are obtained as 0.36 (MMetric tons/ billion US$) for 2007 and 0.31 (MMetric tons/ billion US$) for 2016 (United Nations, 2018). Finally, emission reduction 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 all scenarios are meeting at least 30% emission reduction target compared to 2007 value (CO_2 per GDP) in the scenario descriptions.

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

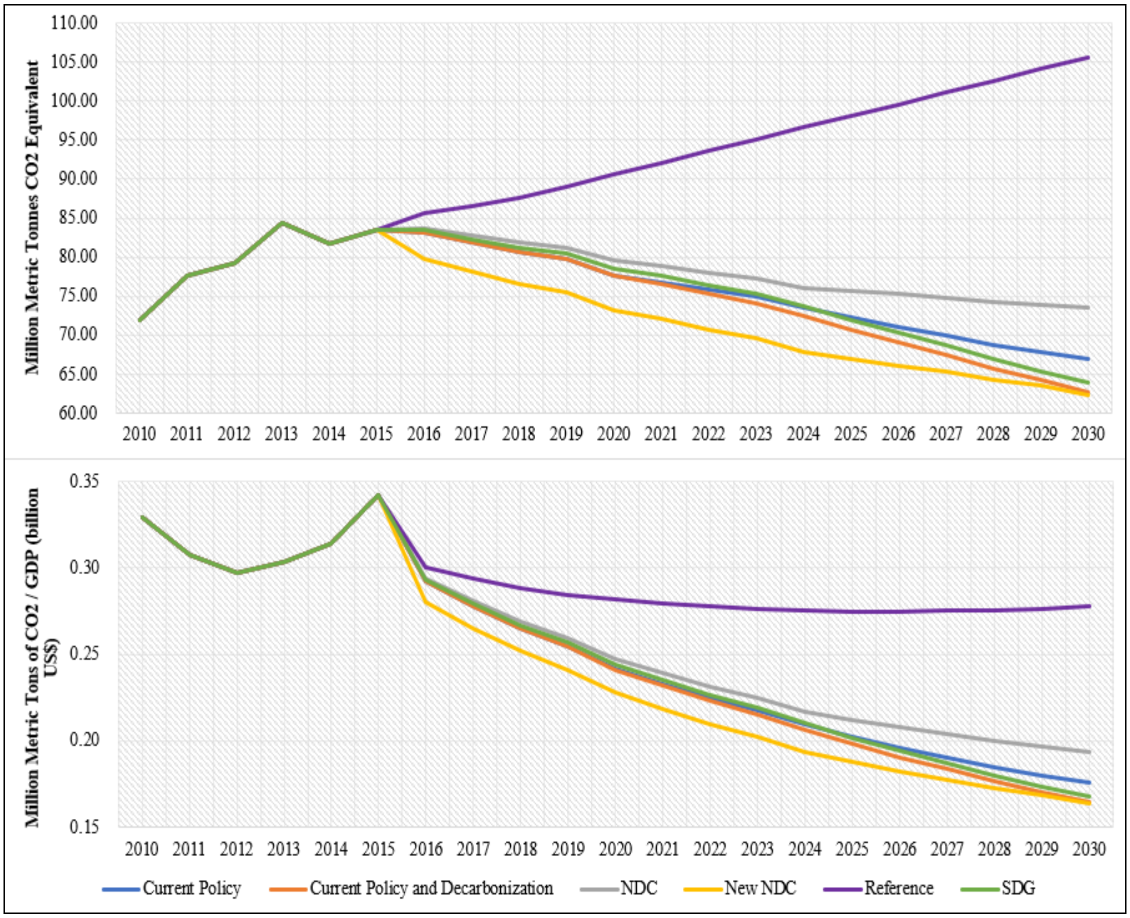


Figure 5- 5:CO_2 emission without LULUCF (MMetric Tonnes of CO_2) and CO_2 emission per GDP (MMetric Tonnes of CO_2 / Billion US$)

Although most of the scenarios meet the emission targets for 2030, it is important to analyse the contribution of sectoral emissions. Figure 5-6 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 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 demand side, which means demand-side policies in the new NDC scenario proved to be more successful in reducing emissions.

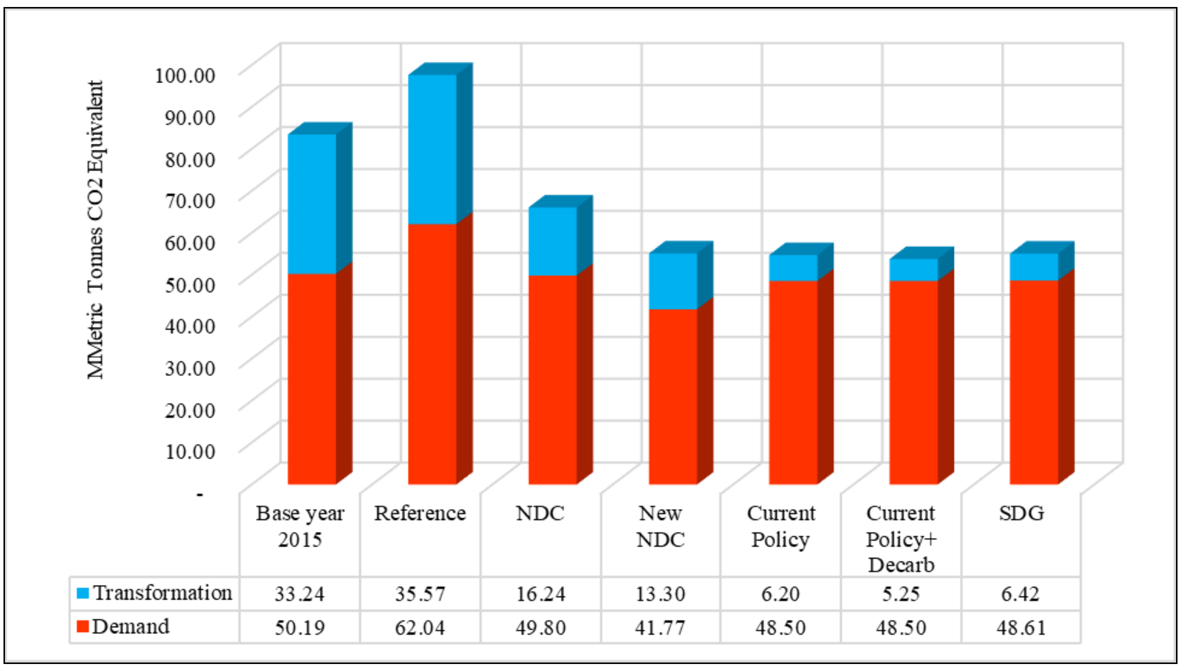


Figure 5- 6:Emission comparison for scenarios by demand and transformation in 2030

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 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.

In addition to the sectoral emission contribution, it is important to analyse emissions by fuel for each scenario. Figure 5-7 presents demand-side CO_2 emission comparison of scenarios by fuels by 2030 and base year 2015. Reference scenario has the highest demand-side emission production, which is followed by 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 has also a direct contribution to emissions of the demand side. Also, other industry sector has major consumption of oil, diesel, natural gas, LPG and coal which contributes emissions obviously.

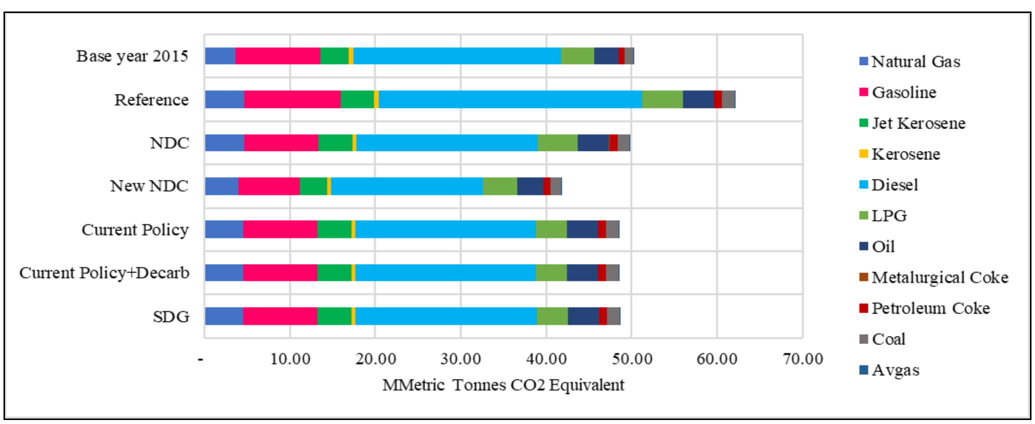


Figure 5- 7: Demand-side CO_2 emission comparison of scenarios by fuels by 2030

Besides 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 5-8. 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 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 decarbonization scenario by 2030.

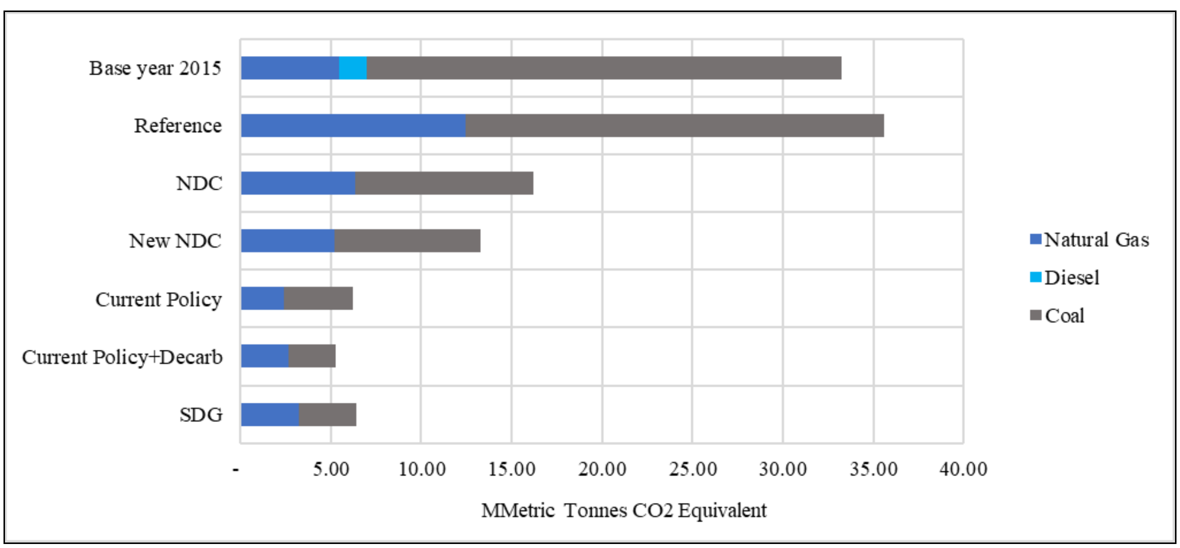


Figure 5- 8: Transformation side CO_2 emission comparison of scenarios by fuels by 2030

Figure 5-9 shows the capacity projection for each scenario between 2010 and 2030. Reference scenario has only biomass, coal, diesel, gas, solar PV, hydro, wind and cogeneration power plants. Real installed capacity values were entered to the LEAP until 2018 for all scenarios.

Also, the capacity between 2018 and 2030 is increased based on 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 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 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 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 (Comision Nacional de Energia Electrica, 2019) 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 (Quiroga et al., 2019; Verastegui et al., 2019).

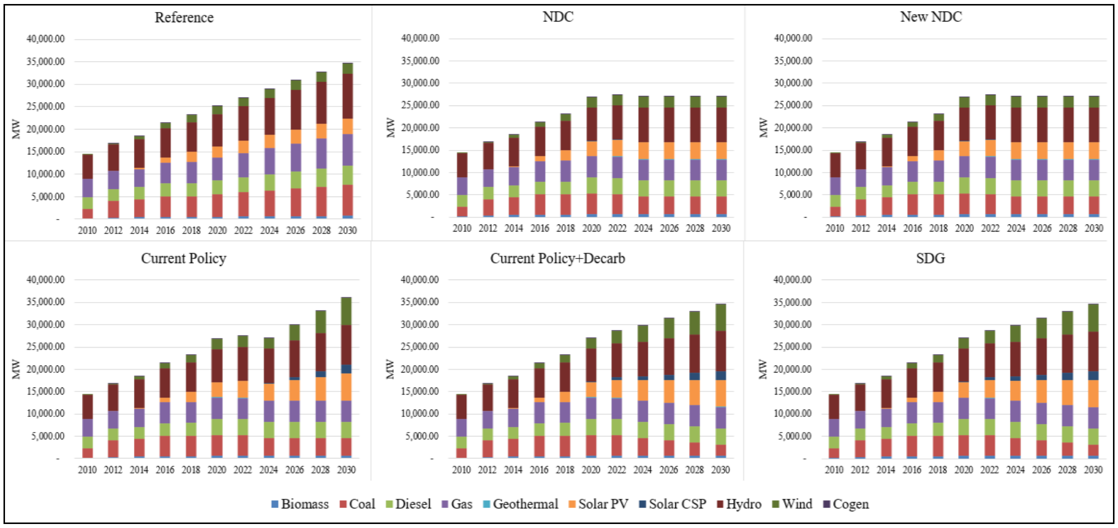


Figure 5- 9: The capacity projection for each scenario between 2010 and 2030

Besides emission targets, renewable electricity generation percentage is mentioned in the scenarios as another target to compare. Figure 5-10 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 is mostly generated from coal, hydro and gas power plants and renewable generation share was 38%. The model results showed that reference scenario has the similar fuel combination as 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, current policy has target to have 60% renewable electricity generation by 2035 (Comité Consultivo de Energía 2050, 2015; Ministerio de Energía, 2018). 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 country´s national resources and self-sufficiency are crucial elements to increase the energy reliability and reduce external dependence in Chile.

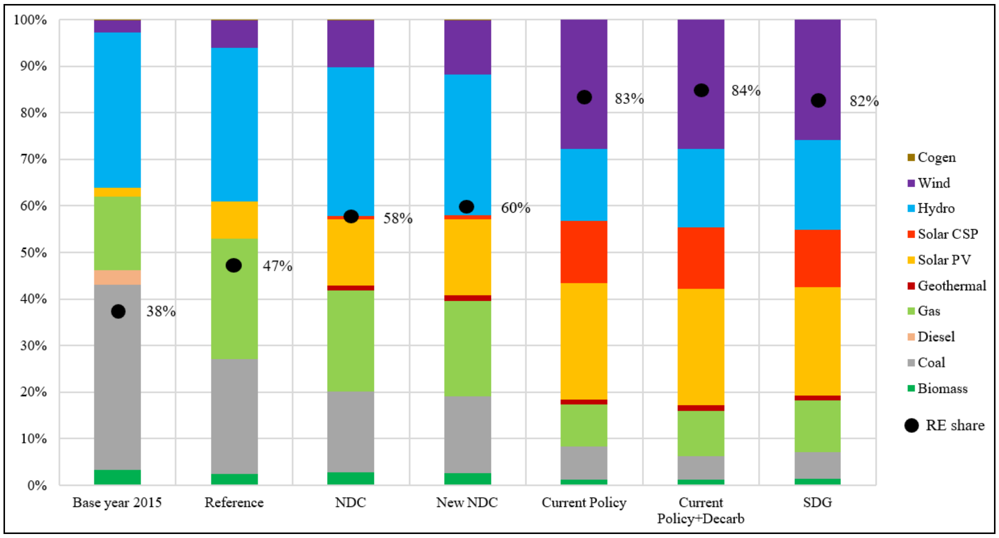


Figure 5- 10:Generation percentage by fuel and renewable energy share for each scenario at 2030

When current policy+decarbonizacion scenario is compared to reference scenario, the production of decommisioned coal power plants is replaced with renewable energy (solar and wind) sources. Also, wind, PV solar, CSP solar and hydro power 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.

5.4. Conclusion

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 analysing 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 38.5% reduction in energy demand when it is compared to 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 current policy scenario. NDC scenario has 20% of total energy demand reduction when the current policy has 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 NDC scenario.

The results indicated 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. SDG scenario showed superior value for the public and commercial sector due to requiring more energy by 2030 to meet targets. Also, mining and other industry sectors have significant demand reduction in the new NDC scenario due to its considerable demand decrease in all sectors. Finally, transportation sector share reaches 35% for NDC and new NDC scenarios, and 38% for current policy and SDG scenarios when it is obtained 32%

for reference scenarios in total energy demand share due to electricity demand increase by 2030.

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 52.9% emission reduction when they are compared to 2016 value, that means they are also meeting the 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, demand sector has a major contribution to the emissions in Chile when it is compared to transformation sector. The results showed that even though emissions from transformation sector demonstrate a significant reduction by 2030 in different scenarios, the decrease in demand side is not clearly noticed. Therefore, Chile also requires appropriate energy efficiency and renewable energy policies to be implemented for demand sides of transport, mining and other industries to reduce emissions at demand-side as it has decarbonization plan for transformation side. Reference scenario has the highest demand-side emission production, which is followed by NDC scenario when new NDC has the lowest value near 40 million metric tonnes of CO_2 emissions.

Also, when the main sectors in demand are evaluated, the transport has the largest contribution to emissions and it is followed by industry, mining, public and commercial, and residential sector, respectively. When fuel contribution to emission is considered, diesel has the main contribution to the emissions, followed by gasoline, natural gas, LPG, jet kerosene, and oil. Diesel, jet kerosene and gasoline fuels usages in the transport sector have a significant contribution to emission. Diesel usage of the mining sector and major consumption of oil, diesel, natural gas, LPG and coal in industry sector also contribute to emissions directly.

NDC, new NDC, current policy, current policy+decarbonization and SDG scenarios showed essential emission reduction in 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 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 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. Therefore, it demonstrates 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 less emissions and more diversification in terms of energy production.

This study has some limitation due to the nature of the research methods applied, the time and resource constraints, and finally due to the 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 due to time constraints 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 technology and emissions data in LEAP´s database 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 the regions separately (SEN, SEA, SEM) and adding more futuristic technologies to the model to see their impact on the energy system in Chile.

5.5. Summary of the chapter

In chapter 5, energy and environmental model is generated by using LEAP to forecast energy demand, supply and emissions for Chile by 2030 and create scenarios considering different policies motivated by current policy, national and international commitments of Chile. 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 the transformation sector.

Although emissions from transformation sector demonstrate significant reduction by 2030, the 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, PV solar, CSP solar and hydro power 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.

6. CONCLUSION

The major conclusions of this research associated with each chapters (including journal paper) answer to the first, second, third and fourth specific objective of this dissertation, and they are the listed as follows:

- Promoting renewable energy and energy efficiency are popular ways for countries to reach their energy and environmental goals and for decarbonization and decontamination in the future energy matrix. Chile became successful in promoting renewable electricity production without fiscal incentives or FITs. Nevertheless, encouraging the mining and industry sector with obligatory regulations, using public finance for the residential sector, and mandatory economic instruments for the transport sector can be useful to increase the renewable energy share in all energy sectors (Chapter 2).
- Adoption of energy efficiency in several energy sectors is another substantial matter to achieve a sustainable energy future. Chile has mandatory energy efficiency labelling for appliances, energy codes, and efficiency standards for social housing and private residential buildings. However, there are no regulations for non-residential and commercial buildings and the efficient and clean use of firewood. In the Chilean industrial sector, only voluntary actions are found. In the transport sector, an energy efficiency label for new light-duty vehicles has been mandatory since 2013. Chile has mostly voluntary support mechanisms for energy efficiency. Nonetheless, mandatory and economic support mechanisms are also necessary for specific sectors. More laws, regulations, codes, and standards must be implemented by the government in the industry, mining, and transport

sectors to reach the national target. The combination of renewable energy instruments with energy efficiency instruments can produce a substantial impact (Chapter 2).

- Solar and wind technology had more capacity increase than biomass and mini-hydro in the latest years. Also, the capacity of solar PV and wind technologies showed a significant increase after 2013. Renewable energy-related laws implemented between 2012 and 2017 could have the best impact on promoting solar energy technologies due to its positive PEIs. Policies to promote wind and mini-hydro technologies could be less effective than solar energy due to having lower PEIs. Energy policy to promote biomass also seems insufficient with its irregular PEIs for different years. Additionally, PV and CSP technologies showed a significant reduction in LCOE in the last eight years due to technological developments (Chapter 3).

- Legislative policy “the significant target for renewable energy capacity increase (70% of new capacity renewable energy installation target between 2015 and 2050)” was found the best policy between all policy alternatives according to experts´ assessment. Under the monetary policy, solar subsidies for the residential sector was obtained as the best option. Finally, regulation for solar thermal technology had as the highest score between regulatory policy alternatives. Otherwise, a monetary policy about subsidizing pre-feasibility and pre-investment studies for renewables had the lowest overall score between all alternative policies, which means the experts do not find pre-feasibility incentives useful to promote renewables anymore (Chapter 3).

- Chile meets sixteen targets without needing any interventions by 2030 between twenty-four energy-related sustainable development targets. As the analysis shows, Target 2.1, Target 5.b, Target 12.3, Target 13.1, and Target 17.6 require extra energy to be encountered by 2030. When all SDGs are considered to be met by 2030, it is found that energy demand for 2030 SDGs was calculated as 1,463.08 million GJ due to additional energy requirement to meet SDGs. When benchmarking is considered with Targets 7.3 and 8.1, total energy demand is calculated as 1,618.87 million GJ by 2030. In this study, if there is no target for a specific indicator in Chile, additional energy is not considered. However, Target 2.4 and Target 12.5 may save energy or Target 11.2 may require more energy by 2030, which means that SDGs scenario could result in more or less energy than BAU by 2030 (Chapter 4).

- Due to its significant emission reduction target, the new NDC scenario has at least 38.5% reduction in energy demand when it is compared to reference scenario by 2030. Current policy and current policy+decarbonization scenarios had the same demand value near 980 million GJ. SDG scenario energy demand resulted higher than current policy scenario. NDC scenario has 20% of total energy demand reduction when the current policy has 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 NDC scenario (Chapter 5).

- 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 52.9% emission reduction when they are compared to 2016 value, that means they are also meeting the 45% emission reduction target by 2030 (Chapter 5).

- Although the energy transformation sector contributes to emissions significantly and policies have mostly been implemented to reduce emissions in the transformation sector, demand sector has a major contribution to the emissions in Chile when it is compared to transformation sector. The results showed that even though emissions from transformation sector demonstrate a significant reduction by 2030 in different scenarios, the decrease in demand side is not clearly noticed. Therefore, Chile also requires appropriate energy efficiency and renewable energy policies to be implemented for demand sides of transport, mining and other industries to reduce emissions at demand-side as it has decarbonization plan for transformation side. Reference scenario has the highest demand-side emission production, which is followed by NDC scenario when new NDC has the lowest value near 40 million metric tons of CO_2 emissions (Chapter 5).

- When the main sectors in demand are evaluated, the transport has the largest contribution to emissions and it is followed by industry, mining, public and commercial, and residential sector, respectively. When fuel contribution to emission is considered, diesel has the main contribution to the emissions, followed by gasoline, natural gas, LPG, jet kerosene, and oil. Diesel, jet kerosene and gasoline fuels usages in the transport sector have a significant contribution to emission. Diesel usage of the mining sector and major consumption of oil, diesel, natural gas, LPG and coal in industry sector also contribute to emissions directly (Chapter 5).

- NDC, new NDC, current policy, current policy+decarbonization and SDG scenarios showed essential emission reduction in 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 decarbonization scenario by 2030 (Chapter 5).

- 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 (Chapter 5).

- 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 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 (Chapter 5).

- It demonstrates 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 less emissions and more diversification in terms of energy production (Chapter 5).

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APPENDICES

APPENDIX A: APPENDIX FOR SECTION 3

Table A- 1:List of the survey participants

Government			**16**
	Ministry of Energy	4	
	Energy Sustainability Agency	4	
	National Electric Coordinators	1	
	Corporation for the Promotion of Production	1	
	National Energy Commission	4	
	Ministry of Environment	1	
	Generators of Chile	1	
Academic			**9**
Industry			**5**

Table A- 2:List of Current Policy in Chile

Year	Policy/Law	**References**
2000	Law 19.657 on Geothermal Energy Concessions provide a framework for the exploration and exploitation of geothermal resources through concessions.	(Global Data, 2017; IEA, 2018)
2001	Chile launched a Programme for rural electrification with renewable energy. Six thousand individual PV systems installed, a capacity building program for small business and cooperatives on O&M of renewable energy systems, and over 44 standards issued for solar PV, micro-wind, micro-hydro, and hybrid systems.	(IRENA, 2015b)
2004	Grid access for renewable energy in Chile was facilitated in 2004 by the “Short Law I” (Law 19.940). The law exempted renewable energy producers under 9MW from transmission fees and provided reduced fees for those between 9 and 20 MW.	(Global Data, 2017; IRENA, 2015b)
2005	Law 20.018 requires electricity distribution companies to source power for regulated markets through non-discriminatory auctions (thus including renewables) and allows renewable energy producers to sign long-term PPAs with distribution companies.	(IEA, 2018; IRENA, 2015b, 2015c)
2005	Invest Chile Project partially subsidizes pre-feasibility and pre-investment studies for renewables (support capped at USD 160,000 per project).	(Global Data, 2017; IRENA, 2015c, 2015b)
2007	The minimum energy performance standard for the building envelope was established in 2007 to contribute energy efficiency and is included in the General Ordinance for Town Planning and Construction.	(IEA, 2018)

2007	Fiscal incentives for biodiesel and bioethanol (transportation usage) include an exemption from fuel tax (and alcohol tax in the case of bioethanol), but not of VAT.	(IRENA, 2015c, 2015b)
2008	An initial quota of 5% renewable electricity in 2014 to be increased by 0.5% yearly increments until 2024.	(IRENA, 2015c, 2015b)
2008	Technology-specific support for concentrated solar power includes a USD 20 million subsidies for up to 50% of the costs of one project through the support for Non-Conventional Renewable Energy Development Programme.	(IRENA, 2015b)
2008	Regulations are in place allowing the blending of bioethanol and biodiesel with gasoline and diesel (in transportation) respectively at 2% or 5%.	(IRENA, 2015b)
2008	Chile implemented the Non-Conventional Renewable Energy Law to encourage the development of sources such as solar, wind, biomass, geothermal, tidal, and hydroelectric plants. The Non-Conventional Renewable Energy Law (Law 20.257) aims to fulfill future energy requirements by developing nonconventional renewable sources for electricity generation, such as geothermal, wind, solar, tidal, biomass and small hydroelectric plants.	(Global Data, 2017; IEA, 2018; IRENA, 2015b)
2009	The regulatory framework for solar water thermal (Law 20.365) provides technical standards, certification systems for solar water heating systems. Incentives include tax exemptions ranging from 20% to 100% on a progressive scale based on property value.	(IRENA, 2015c, 2015b)
2009	Program for rural and social energy was launched to expand the provision of energy for public services and to develop energy solutions for productive uses, principally in isolated areas. Priority is given to renewable sources, mainly solar energy in the north and center of the country and small hydro and wind in the central-south regions.	(IRENA, 2015b)
2010	The General Environmental Law (Law 20.417) established the environmental assessment system, sets emission and quality standards, and creates prevention and decontamination plans.	(IEA, 2018)
2010	Providing tax breaks for businesses and end-users for installing water-heating thermal panel.	(Global Data, 2017)
2011	In 2011, Chile established a voluntary comparative energy label for residential buildings, with categories that ranged from “A” (highest efficiency) to “E” (lowest efficiency), with “E” corresponding to the minimum standard for the building envelope	(IEA, 2018)
2011	The Ministry of Energy has a range of energy efficiency policies for public buildings. Since 2011, the Energy Efficiency in Public Buildings Programme has provided technical support through energy audits, implementation, measurement and verification, as well as capacity building for energy efficiency projects in existing public buildings.	(IEA, 2018)
2011	The government had opened 5,736 hectares of land to be obtained for the development of wind farms through tendering.	(Global Data, 2017)
2012	A net metering scheme for consumers under-regulated electricity tariffs was established. The scheme applies to renewable energy and cogeneration systems of up to 100kW.	(IRENA, 2015c, 2015b)

2012	Subsidizing transmission lines for renewable energy projects.	(Global Data, 2017)
2012	The Invest Chile Project was continued in 2012 by the Support for Non-Conventional Renewable Energy Development Programme, with a USD 85 million budget. The 2014-2018 Energy Programme aims at strengthening support schemes for pre-investment in renewable electricity generation.	(IRENA, 2015c, 2015b)
2012	The national plan for PV pumping from the ministry of agriculture provided subsidies of up to 90% of installation costs to farmers.	(Global Data, 2017)
2012	Financial support from the Chilean Economic Development Agency (CORFO) had a key role in enabling the establishment of the Research Centre for Solar Energy Technologies, focused on applied R&D.	(IRENA, 2015b)
2012	The Energy Efficiency Action Plan 2012–2020: The National Energy Strategy intends to reduce the energy intensity of Chile by 12% by 2020.	(Global Data, 2017)
2013	Non-Conventional Renewable Energy Law amended in 2013. The 2013 amendment mandates that electric utilities with more than 200 MW operational capacity should generate 20% of electricity from renewable sources by 2025; and for companies that can produce energy on their own or by contracting from third parties, it establishes an increasing obligation of 0.5% annually, to reach 10% in 2024.	(Global Data, 2017; IEA, 2018; IRENA, 2015b)
2013	The so-called "20/25 Law" (Law 20.698) targets to generate 20% of Chile's electricity from renewable sources by 2025, excluding hydropower plants over 20 megawatts (MW). Chile has a target to generate 20% of its electricity from renewable sources by 2025.	(IEA, 2018; IRENA, 2015b, 2015c)
2013	An energy efficiency label for new light-duty vehicles and their associated incentives has been mandatory since 2013	(IEA, 2018)
2013	A new public auction system complementing the existing quota obligation. The new system allows for public auctions on years when it is anticipated that renewable electricity quota will not be fulfilled. The auctions will be technology neutral (amongst renewables) and based exclusively on price, providing a 10-year PPA. The price of the auction will be capped at the projected cost of "efficient expansion" of capacity at nodal point.	(IRENA, 2015b)
2013	Geothermal energy concessions (technology-specific support) provides a clear regulatory framework for geothermal exploration and development, with specific provisions addressing potential overlaps with mineral rights.	(IRENA, 2015b)
2013	In 2013, the process for grid extension was streamlined by the Electrical Easement Act (Law 29701). The 2012 Support for Non-Conventional Renewable Energy Development Programme aims at subsidizing transmission lines for renewable energy projects.	(IRENA, 2015b)
2014	In 2014, the Ministry of Energy in coordination with the Ministry of Health introduced an energy efficiency-improvement programme for all hospitals defined as High Complexity Hospitals	(IEA, 2018)
2014	The net billing law (Law 20.571 of 2014) basically grants users the right to sell their surplus directly to the grid (electricity distributor) at a regulated price.	(IEA, 2018)

2014	In October 2014, Chile enacted the first climate pollution (carbon) tax in South America (Law 20.780) (except biomass). This green-taxes reform imposes an annual tax on emissions from boilers and turbines with a thermal input of at least 50 MW and entered into force in 2017.	(Global Data, 2017; IEA, 2018; IRENA, 2015b, 2015c)
2014	In 2014, the Ministry of Energy, supported by German BMUB-GIZ, launched the Public Solar Roofs Programme (PSRP) to stimulate the market for rooftop PV solutions by organizing tenders to encourage demand from public buildings.	(IEA, 2018; IRENA, 2015b)
2014	The electricity generated by hydropower projects under 20MW is eligible for Chile’s quota obligation. Hydropower projects between 20MW and 40MW are partially eligible.	(IRENA, 2015b)
2014	Promotion the sustainable development of hydropower including through new environmental legislation and land use planning in river basins.	(IRENA, 2015c)
2014	Extension and improvement of the financial incentives for solar water heating, as well as providing subsidies for installation of solar water heaters in the reconstruction of disaster-affected areas (Arica, Iquique and Valparaíso).	(IRENA, 2015c)
2014	Promotion of the use geothermal energy for low and medium temperature uses such as domestic and commercial heating.	(IRENA, 2015b)
2014	Creation the “Firewood Boards” at the national and regional levels to address safety, equity, environmental and economic aspects of the use of firewood for heating. Improvement of market information about biomass, productive development and increased quality standards through regulation.	(IEA, 2018; IRENA, 2015b)
2014	Energy Access Fund creates three grant funds for the installation of renewable energy systems, local capacity building, and innovative technical solutions to meet small-scale energy demands.	(IRENA, 2015c, 2015b)
2014	The ministry of agriculture dedicated USD 2.2 million to co-financing for renewable energy projects for productive uses in agriculture and forestry.	(Global Data, 2017)
2014	The 2014 National Energy Agenda set a new and more-ambitious energy efficiency target of reducing TFC by 20% by 2025 compared with a business-as-usual (BAU) scenario. In 2015, TFC was 8% below BAU (2010 baseline).	(IEA, 2018)
2014	In 2014, the Ministry of Energy introduced certification for firewood stoves of specific sizes that establishes emission limits for particulate matter.	(IEA, 2018)
2014	To encourage installing solar water heaters (SWHs) for residential water heating: a subsidy to incorporate SWH into housing reconstruction programmes (2014-17)	(IEA, 2018; IRENA, 2015c)
2015	A mandatory energy efficiency label was introduced for firewood stoves (2015) and pellet heaters (2017) to help consumers make an informed decision based on energy performance.	(IEA, 2018)

2015	In 2015 the Ministry of Energy published the National Energy Policy 2050 which includes a broad set of energy efficiency targets for 2035 and 2050, including -70% of the main categories of appliances and equipment sold in the market are considered efficient.-All procurement of public passenger transport vehicles must include energy efficiency criteria as part of the evaluation.-100% of new public and residential buildings apply Organization for Economic Co-operation and Development (OECD) standards for efficient buildings.	(IEA, 2018)
2015	The introduction of the new tender's law (Law 20.805) in 2015 aims to reduce electricity tariffs and encourage market competition.	(IEA, 2018)
2015	At least 60% of electricity generation target by 2035.	(IEA, 2018)
2015	70% of new capacity renewable energy installation target between 2015 and 2050.	(IEA, 2018)
2015	In 2015, the Ministry of Energy launched their milestone policy for use of wood and derivatives for Heating to limit air pollution from burning firewood, diversify energy sources and promote independence from energy imports. The policy aims to transform the firewood market into a formal one that contemplates the sustainable production of firewood for energy and its efficient use.	(IEA, 2018)
2015	The regulation that sets the requirements for efficient CHP plants (below 20 MW) was formally approved in May 2015 (Decree No. 6 of the Ministry of Energy on Efficient Cogeneration). Regulated final customers that own efficient CHP facilities are covered under the distributed generation policies, are eligible to net billing and receive priority (depending on the fuel source) to dispatch their energy surplus to the distribution network.	(IEA, 2018)
2016	The Equity in Tariffs Law (Law 20.928 of 2016) established mechanisms of equity in the tariffs of electricity services.	(IEA, 2018)
2016	Law 20.936, the Transmission Law established the new National Transmission System (to replace the Trunk Transmission System) and created the National Electricity Coordinator that supports the grid expansion and the interconnections between the transmission grids, and modifies the transmission toll payments to foster renewables. An explicit objective of the 2016 Transmission Law is to encourage renewable electricity generation.	(IEA, 2018)
2016	In January 2016, Chile auctioned 3 000 hectares of public land with a high resource potential for the construction of renewable-energy projects in several locations	(IEA, 2018)
2016	The NCRE loan has been available for banking since April 2016.	(IEA, 2018)
2016	In 2016, the Ministry of Energy created a programme to promote the direct use of geothermal energy for heating applications	(IEA, 2018)
2017	Chile ratified the Paris Agreement and committed to developing policies on climate change and to achieve sustainable development targets. Chile's related National Determined Contribution (NDC) is to reduce the CO_2 intensity of GDP by 30% from the 2007 levels unconditionally by 2030, and by 35% to 45%, subject to international financial support.	(Global Data, 2017; IEA, 2018)

2017	In April 2017, the Ministry of Energy launched a new and more-ambitious energy efficiency seal (with three categories: bronze, silver and gold) to recognize energy efficient companies of all sizes, including industrial companies. The seal programme aims to reward the leading companies that are committed and invest in energy efficiency to reduce their energy costs and increase their competitiveness.	(IEA, 2018)
2017	In January 2017, the Ministry of Energy launched Gestiona Energia, a mandatory programme under which all public services from the central government are obliged to have a certified energy manager and have to measure the energy consumption and energy intensity of all their buildings.	(IEA, 2018)
2017	In June 2017, the energy efficiency label scope was extended to medium-duty vehicles up to 3 600 kilograms (kg), and to electric and hybrid vehicles.	(IEA, 2018)
2017	The MTT is subsidizing the replacement of taxis with higher-efficiency vehicles, with a limit of a CLP 6.5 million subsidy for a new electric taxi. The funding allocated to the subsidies is determined on a regional level. The MTT (from 2017) also supports the introduction of electric buses in Santiago	(IEA, 2018)
2017	A mandatory energy efficiency label was introduced for and pellet heaters (2017) to help consumers make an informed decision based on energy performance.	(IEA, 2018)
2017	In April 2017, the government also launched a district energy strategy to tackle the use of firewood for heating and further improve the air quality at the local level, particularly in the southern regions.	(IEA, 2018)
2017	To encourage installing solar water heaters (SWHs) for residential water heating: a tax exemption for SWH installation in new housing (from 2017)	(IEA, 2018; IRENA, 2015c)
2017	Regulation on biogas plant safety was published in February 2017 and entered into force in August 2017. It introduces the minimal safety requirements for biogas plants; regulates the stages of design, construction, operation, maintenance, inspection and end of operations; standardizes the direct thermal use and combustion of biogas for to generate electricity, as well as flaring.	(IEA, 2018)

APPENDIX B: APPENDIX FOR SECTION 4

Table B- 1:Energy-related SDGs, targets and indicators to measure the goals (Santika et al., 2019; United Nations, 2019b)

ENERGY-RELATED SDGs: (Santika et al., 2019)		**Indicator assessment for Chile 2030:** (OECD, 2019; United Nations, 2018)	**Energy Intensity (EI):**	**Additional 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 (The World Bank Group, 2017a) 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} (Santika et al., 2019) EC_f = The food energy content of cooked potato = 930.00 kcal/kg (USDA, 2018) $Eon_{farm, max}$ = On-farm agriculture energy usage= 0.005 GJ/kg (Smil, 2008) $Eoff_{farm, max}$ = Off-farm agriculture energy usage= 0.010 GJ/kg (Smil, 2008) 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*
Target 2.3	Indicator: Cereal yield (Kg per hectare)	Data for cereal yield in Chile is accessed between 2009-2013 (The World Bank Group, 2017a). The growth rate is calculated as 6.07% based on available data. By considering the calculated growth rate, cereal yield in 2030 is calculated 14582 (kg/hectare), which is more than planned value to double the agricultural production.	The target aims to double the agricultural productivity compared to 2015, which means Chile should increase cereal yield from 7082 (kg per hectare) to 14164 (kg per hectare) by 2030.	*Calculated cereal yield for 2030 is obtained more than planned value to double the agricultural production. Therefore, it is assumed that the target will be met in 2030.*

Target 2.4	Indicator 2.4.1: Proportion of agricultural are under productiveve and sustainable agriculture	Data: 2000-2016 (The World Bank Group, 2017b) Based on the growth rate of 0.26% which is obtained between 2000 and 2016 for Chile, the total agricultural area for 2030 is calculated as 16,316,256.50 m^2.	A country which has sustainable agriculture targets will have 26.85% less energy per hectare than conventional agriculture (Alluvione et al., 2011). Based on the literature, the approximate energy saving= 2.225 GJ*hectare^{-1}*year^{-1} when sustainable agriculture is considered (Fischer-Kowalski, 2008; Santika et al., 2019).	*There is no target for Chile to make agriculture more sustainable. Therefore, E_total_saving=0 GJ*
Goal 3. Ensure healthy lives and promote well-being for all at all ages				
Target 3.8	Indicator 3.8.2: The number of people spending more than 10% of household consumption or income on out of pocket health care expenditure or income	Data: 1997-2006 (The World Bank Group, 2017a) CAGR: 15.69%		*Based on the CAGR 15.69% which is calculated from available data between 1997 and 2006 for Chile, 100% of the population will spend money on health in 2030 without any intervention, which means additional energy is not required to meet this target.* *E_required_total = 0 GJ*
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all				
Target 4.1	Indicator 4.1.1: Primary and secondary school enrollment ratios (% gross)	The first target in this goal is assessed by indicators of primary and secondary school gross enrolment ratios (The World Bank Group, 2017a). It is assumed that primary education is for children aged 7 to 12 and secondary education is for children aged 12 to 18 (Corsi-Bunker, 2011). Primary school enrolment (% gross) in Chile was informed at 99.8 % in 2016, according to the World Bank (The World Bank Group, 2017c). Moreover, secondary school enrolment in Chile (% gross) is 84.42% in 2000 and 99.66% in 2017 (The World Bank Group, 2017d). The growth rate calculated based on available data (CAGR= 0.98%) shows that the secondary school enrolment in Chile will reach 100% before 2030.		*Target "primary school education for all" is already achieved before 2030.* *With the calculated growth rate, secondary school enrollment ratios (% gross) will also reach 100% by 2030.* *E_required_total = 0 GJ*
Target 4.2	Indicator 4.2.1: Pre-primary school enrollment (% gross)	Pre-primary school enrolment (% gross) data is obtained between 2013 and 2017 for Chile (The World Bank Group, 2017a). The growth rate is calculated as 2.15% with available data, and it was obtained that the target for 100% pre-primary school enrolment will be met in 2030 in Chile.		*Preprimary school enrollment will reach 100% in 2030 without any intervention. There is no surplus energy requirement to meet the target.* *E_required_total = 0 GJ*
Target 4.3	Indicator 4.3.1: School enrollment in tertiary education (% gross)	In Chile, the values for this indicator are obtained 36.22% in 2000 and 91.47% in 2017 (The World Bank Group, 2017a). CAGR between 2000 and 2017 is calculated with equation (1) and found as 5.60%.		*This growth rate shows that the target (100% enrollment) will be met before 2030 for tertiary education.* *E_required_total = 0 GJ*

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 (eMarketer, 2016) CAGR= 1.18% Population without a mobile phone in 2030= 5,130,570.70 people	EI for owning a mobile phone (Carroll and Heiser, 2010; Santika et al., 2019): 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 additional energy requirement when all population own a mobile phone by 2030: E_required_total =26,627.66 GJ*
Goal 6. Ensure availability and sustainable management of water and sanitation for all				
Target 6.1	Indicator 6.1.1: Proportion of population using safely managed drinking water services	The improved water source mentioned in the target means being accessible on-premises, available when needed and free from faecal and priority chemical contamination including piped water, boreholes or tube wells, protected dug wells, protected spring and packaged or delivered water (The World Bank Group, 2017a). For Chile, proportions of the population using safely managed drinking water is available between the years 2000 and 2015, which are 91.57% and 98.15%, respectively (The World Bank Group, 2017a). The growth rate is calculated 1.48% based on available data.		*Based on the calculated CAGR, 100% of the population will reach safe drinking water in 2030 without any intervention. E_required_total = 0 GJ*
Target 6.3	Indicator 6.3.1: Proportion of wastewater safely treated	Data= 2000-2015 (OECD data, 2019) The proportion of wastewater safely treated is increased significantly between these years as follows: 20.90% and 99.93%, accordingly (OECD data, 2019). The calculated growth rate (CAGR= 10.99%) shows that the target “100% wastewater treatment” is met before 2030 for this target in Chile. The additional energy requirement to meet this target is zero.		*The proportion of wastewater treatment is already reached 100% in 2017. Thus, the target is already met before 2030. E_required_total = 0 GJ*

Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all				
Target 7.1	Indicator 7.1.1: Proportion of population with access to electricity	Data= 2000-2016 (The World Bank Group, 2017a) The first indicator for Target 7.1 "100 % electricity access" is already met in Chile by 2016 (The World Bank Group, 2017a).		*Target 7.1 "100 % electricity access" is already met in Chile by 2016.* *E_required_total = 0 GJ*
	Indicator 7.1.2: The proportion of the population which accesses clean technologies for cooking	Data for Chile is available between 2000 and 2013, which shows that the ratio increased from 86.10% 91.67% in thirteen years (The World Bank Group, 2017a). The calculated growth rate (0.48%) shows that 100% of the population will access clean cooking technologies in 2030 without any intervention.		*Based on the calculated CAGR, 100% of the population will access clean cooking technologies in 2030 without any intervention.* *E_required_total = 0 GJ*
Target 7.2	Indicator 7.2.1: Renewable energy share in the total final energy consumption	The renewable electricity production in Chile showed an increasing trend, which was increased from 15% to 19,92% from 2015 to 2018, respectively (IRENA et al., 2018; Renewable Energy Policy Network for the 21st Century (REN 21), 2018).	The share of renewable energy is related to energy. However, the target does not affect the final energy consumption.	*Additional energy requirement or saving is not considered to calculate for this target.* *E_required_total = 0 GJ*
Target 7.3	Indicator 7.3.1: Energy intensity measured in terms of primary energy and GDP	Data= 2000-2015 (The World Bank Group, 2017a) CAGR= -1.40% EI at 2030= 3.058 (MJ/2011 PPP GDP)	This target aims to double the global rate of improvement in energy efficiency based on 2010 (United Nations, 2019b). Until 2010, the global rate of improvement in energy efficiency was 1,3%. Therefore, CAGR was expected at 2.6% between 2010 and 2030 and global EI needs to be reduced to 3.422 MJ/$2011 PPP GDP by 2030.	*EI at 2030 for Chile= 3.058 (MJ/2011 PPP GDP) which is better than the global targeted value (3.422 MJ/$2011 PPP GDP) in 2030. Therefore, the target will be met before 2030.*
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all				
Target 8.1	Indicator 8.1.1: Annual growth rate of real GDP per capita	Data= 2000-2017 (The World Bank Group, 2018) CAGR= 2.80%. GDP per capita for 2030= 32,592.96 $ 2011 PPP/cap.	The target aims that energy intensity in 2030 will be 3.422 MJ/2011 PPP GDP for Chile in parallel to the global target (The World Bank Group, 2017a)	*TPES 2030= 2,312,671,558.63 GJ* *By considering 70% conversion to supply to demand in National Energy Balance in Chile* (Comision Nacional de Energia, 2019) *Total energy demand in 2030= 1,618,870,091.04 GJ*

Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation			
Target 9.1	Indicator 9.1.1: “Rural Access Index (RAI)” which is the share of rural people who live within 2 kilometers (about 20 – 30 minutes walking time) of the nearest all-season road (Eqbali et al., 2017)	For Chile, RAI (% of rural population) was obtained for 2002 and 2004, which are 59% and 76%, respectively (Fay and Morrison, 2005; The World Bank, 2004). With these available data, the growth rate is calculated 12.63% and it shows the target “100% of the rural population access to roads” will be met by 2030.	*The target “100% of rural population access to roads” will be met by 2030 by considering calculated growth rate for Chile.* *E_required_total = 0 GJ*
Target 9.c	Indicator 9.c.1: The proportion of population covered by a mobile network, by technology	Mobile network coverage (% population) in Chile: 100% by 2012 (GSM Association, 2007).	*The target for 100 % of the population covered by a mobile network in Chile is already met before 2030.* *E_required_total = 0 GJ*
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable			
Target 11.1	Indicator 11.1.1: Proportion of urban population living in slums, informal settlements or inadequate housing	In 2005, 9% of the urban population and in 2007, 1% of the total population lives in slums in Chile (Brain et al., 2009; The World Bank Group, 2017e). The population living in slums during last years in Chile reduced significantly. Therefore, the target which is “none of the population lives in the slums by 2030” will be reached before 2030.	*The target which is “none of the population lives in the slums by 2030” will be reached before 2030.* *E_required_total = 0 GJ*
Target 11.2	Indicator 11.2.1: Proportion of population uses public transport	The proportion of the population uses public transport in Chile was announced at 29.10% in 2012 with a 0.5% annual decrease between 2001 and 2012 (El Ministro de Transportes y Telecomunicaciones, 2015). By considering this negative growth rate, only 20.10% of the population is expected to use public transportation in 2030. Expected proportion of population uses public transport in 2030= 20.10%	*In Chile, there is no target to encourage people to use public transportation in 2030.* *Therefore, energy contribution is not considered for this target.*
Target 11.6	Indicator 11.6.1: Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities	When generation and collection of solid urban waste data are investigated for Chile, it is found that all generated solid waste is collected from cities in Chile based on the available databases (OECD data, 2018; OECD iLibrary, 2018; UN data, 2018). It is also assumed that all regularly collected wastes have adequate final discharged in Chile.	*The target “100% urban waste collection” will be met before 2030.* *E_required_total = 0 GJ*

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 (FAO, 2011). The targeted food loss (L_half) will be 110 kg/cap/year.	The energy intensity (EI) (Santika et al., 2019): $$EI = (EC_{storing} + EC_{retailing}) * L\_half$$ 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*
Target 12.5	Indicator 12.5.1: National recycling rate, tons of material recycled	The recycling rate of total waste in Chile is obtained at 0.4% in 2009 and 1% in 2013 (OECD, 2015; United Nations, 2011). Based on available data, it is calculated that 56.95% of the total produced waste will be recycled in 2030. However, there is no target for the recycling ratio of produced wastes by 2030 in Chile. Therefore, energy-saving by meeting this target is not considered.	If this target is considered for a country, the net energy reduction potential of recycling can be assumed as 1.64 GJ/tonnes as mentioned in the literature (Beigl and Salhofer, 2004; Cleary, 2009; Santika et al., 2019).	*There is no target for recycling ratio of produced wastes by 2030 in Chile. Therefore, energy saving by meeting this target is not considered.* *E_total_savings= 0 GJ*
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 (Barrionuevo and Robbins, 2010; NRC and IDMC, 2015). 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 $GJ*cap^{-1}*year^{-1}$ (Santika et al., 2019).	*Thus, the additional energy requirement to replace affected people after the disaster in Chile is calculated:* *E_required_total =1,565,045.18 GJ*

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 (The World Bank Group, 2019). 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 (Santika et al., 2019).	*When the average energy intensity is considered, the additional energy requirement to meet this target (100% of population with broadband subscription) for Chile is:* *E_required_total=3,927,715.51 GJ*
Target 17.8	Indicator 17.8.1: Proportion of individuals using the Internet	Data= 2000-2017 (The World Bank Group, 2017a). CAGR= 10.97%		*Based on the calculated CAGR, the target "100% of population using internet" is expected to be met before 2030 without any intervention.* *E_required_total = 0 GJ*

APPENDIX C: APPENDIX FOR SECTION 5

Table C- 1:Additional demand to meet energy-related Sustainable Development Goals (SDGs) by 2030

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 (The World Bank Group, 2017a) 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} (Santika et al., 2019) EC_f = The food energy content of cooked potato = 930.00 kcal/kg (USDA, 2018) $Eon_{farm,\ max}$ = On-farm agriculture energy usage= 0.005 GJ/kg (Smil, 2008) $Eoff_{farm,\ max}$ = Off-farm agriculture energy usage= 0.010 GJ/kg (Smil, 2008) 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 (eMarketer, 2016) CAGR= 1.18% Population without a mobile phone in 2030= 5,130,570.70 people	EI for owning a mobile phone(Carroll and Heiser, 2010; Santika et al., 2019): 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 (FAO, 2011). The targeted food loss (L_half) will be 110 kg/cap/year.	The energy intensity (EI) (Santika et al., 2019): $\mathrm{EI} = (\mathrm{EC}_{\mathrm{storing}} + \mathrm{EC}_{\mathrm{retailing}}) * \mathrm{L\_half}$ 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 (Barrionuevo and Robbins, 2010; NRC and IDMC, 2015). 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} (Santika et al., 2019).	*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 (The World Bank Group, 2019). 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 (Santika et al., 2019).	*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.*