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Energy 206 (2020) 118021 Contents lists available at ScienceDirect Energy journal homepage: www.elsevier.com/locate/energy Comparison of energy scenario alternatives for Chile: Towards low- carbon energy transition by 2030 Yeliz Simsek a, d, *, Hasret Sahin b, Alvaro Lorca c, Wayan G. Santika d, e, Tania Urmee d, Rodrigo Escobar a a Department of Mechanical and Metallurgical Engineering, Pontificia Universidad Catolica de Chile, Vicu~na Mackenna, 4860, Macul, Santiago, Chile b Technology Faculty, Energy Systems Engineering, Gazi University, Teknikokullar, 06500, Ankara, Turkey c Department of Electrical Engineering, Pontificia Universidad Catolica de Chile, Vicun~a Mackenna, 4860, Macul, Santiago, Chile d Engineering and Energy Discipline, College of Science, Health, Engineering and Education, Murdoch University, Western Australia e Department of Mechanical Engineering, Bali State Polytechnic, Bali, Indonesia article info Article history: Received 8 January 2020 Received in revised form 26 May 2020 Accepted 30 May 2020 Available online 9 June 2020 Keywords: Energy modelling Scenario alternatives Decarbonization

LEAP NDCs SDGs abstract

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

1. Introduction

Climate change is one of the worldwide challenges for humanity in recent years. Human activities in the energy sector are vital to contributing greenhouse gas (GHG) emissions, which are mostly produced by fossil fuel combustion in, particularly, industry, transportation and electricity generation sectors [1]. Approxi- mately 81% of global energy demand is met by fossil fuels including oil, coal, and gas [2]. Growing demand, tentative fuel price, and the rising concern about climate change are pushing countries to have long-term and sustainable energy planning. Therefore, many *

Corresponding author. Department of Mechanical and Metallurgical Engineer- ing, Pontificia Universidad Catolica de Chile, Vicun~a Mackenna, 4860, Macul, San- tiago, Chile. E-mail address: ysimsek@uc.cl (Y. Simsek).

industrialized and developing countries have started to change their future energy plans towards decarbonization by analyzing several alternatives scenarios to see the impact of national and international commitments on energy plans [3]. In parallel to the developments in the world, Chile also began to take actions. After the Chilean Ministry of Energy was created in 2010, activities related to long-term energy planning have accelerated [4,5]. In the latest years, significant improvements in energy policy development can be observed in Chile [3]. MAPS-Chile can be considered as the first project that developed projections and mitigation action plans to reduce greenhouse gas emissions in Chile [6e8]. In 2014, the Energy Ministry of Chile decided to develop an agenda to define a new role for the Chilean government and the goals for future energy policy [9]. Energy Agenda 2050 was fol- lowed by The Road Map (Hoja de Ruta) and Energy 2050 studies which contained the key items of the long-term energy policy as promised in Energy Agenda [10]. In 2017, Chile ratified the Paris Abbreviations CAGR CO2 GHG GJ GW LEAP LULUCF MMetric MW NDCs P&C PV RE SEN SEA SEM SDGs TED UNFCCC USD Compound annual growth rate Carbon dioxide Greenhouse Gas Emissions Gigajoule Gigawatts Long-range Energy Alternatives Planning System Land Use, Land-Use Change and Forestry Million Metric Megawatts Nationally Determined Contributions Public and Commercial Photovoltaics Renewable Energy National Electricity System Aysen Electricity System Magallanes Electricity System Sustainable Development Goals Technology and Environmental Database United Nations Framework Convention on Climate Change US dollars 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/tCO2 for fixed turbines or boilers above 50 MWth [11]. Besides international promises, Chile also set a national target to develop a long-term energy planning every five years for different energy scenarios that include expan- sion of generation and energy demand, in a horizon of at least thirty years [12]. After the elections in 2017, the new government announced Energy Route 2018e2022, in which the main axes of the new energy route were defined as follows: energy modernization, energy with a social seal, energy development, efficient trans- portation, low energy emissions, energy efficiency, and energy education and training [13]. Moreover, promoting renewable en- ergy and energy efficiency were addressed as essential strategies for Chile to reduce emissions and reach its energy and environ- mental goals in various governmental studies [3]. Chile has divided into fifteen regions from north to south, and it has three main electricity grids: National Electricity System (SEN), the Aysen System (SEA), and the Magallanes System (SEM). Among these three grids, the National Electricity System includes thirteen regions and controls 99% of the total electricity supply of Chile [14]. The primary energy supply of Chile mainly consists of oil, coal, natural gas, biomass, hydro, and it has diversified in recent years with the inclusion of renewable energy such as solar, and wind sources. These sources are consumed in five main sectors in Chile: industry, mining, commercial and public, residential, and transport. Industry and transport represent the biggest shares in the total consumption of energy, and mining, which take place mostly in the northern regions of Chile [15,16], and presents heavily energy- intensive activities. Chile mainly depends on imported fuels for energy supply with an approximate proportion of 71% in 2017. Oil is the main energy source in the energy balance, and it is followed by biomass (mainly firewood), coal, natural gas, and hydro, respectively. Chile has considerable renewable energy potential [3]. Espe- cially, the north of Chile has the best worldwide solar energy potential for energy generation, on account of dryness and clear sky [17,18]. According to a joint study by the Ministry of Energy and the German Agency for International Co-operation in 2014, solar photovoltaic (PV) potential was estimated at 1263 GW, concen- trated solar power at 548 GW, wind power at 37 GW (capacity factor of at least 30%), and small hydropower at 12 GW [19,20]. Additionally, it was projected that Chile has a potential of 164 GW from the ocean due to its long Pacific coast, 16 GW from geothermal sources due to containing 10% of the most active volcanoes in the world, and 1.4 GW from biomass sources [21]. After the national and international commitments of several countries in the latest years, studies in the field of energy modelling and planning increased in the literature. There are some recently published studies related to power generation and electricity expansion planning for Chile [22e29]. However, there is no pub- lished research about long-term energy planning, demand and supply forecasting or energy scenario alternatives for Chile including all energy sectors. Additionally, studies which analyze and compare national/international commitments such as nation- ally determined contributions (NDCs), current energy policies and sustainable development goals (SDGs) do not exist in the literature for Chile so far. Although some energy models including current policy and NDCs of countries exist in the literature, implementing sustainable development goals to the energy model is a significant novelty in terms of contribution to the literature. Also, every country which ratified the Paris agreement has its own NDC target and sustainable development goals which reflect in its current energy policy. Therefore, the methodology followed in this research including energy modelling by considering NDC, SDGs and current policy can be applied to those countries and repro- duced to create similar scenarios, and from that, the comparison can be developed to inform the policymakers about the progress and gaps. Motivated by this gap in the

literature, this research contributes to the state-of-the-art by generating energy and environmental model for Chile and analyzing different scenario alternatives which include energy strategies such as current policies, nationally determined contributions, sustainable development goals, and decarbonization. The contributions of this study to the literature can be listed as follows: 1) creating an energy model for all Chilean energy sector to forecast energy demand and supply by 2030 by using LEAP, 2) to analyze different policies, energy-saving potential and decarbonization impact on energy planning for alternative scenarios in Chile such as current policy, NDCs and SDGs, and 3) to evaluate and compare the determined scenarios if they meet their energy and environmental targets. The reminder of the paper is organized as follows: Section 1 is an introduction to the paper which provides a background of the energy sector in Chile, relevance and objectives of the research, and contribution to the literature. Section 2 provides the methodology applied including a revision of long-term energy planning models and studies in the literature, modelling and scenarios for Chile. Section 3 presents and discusses in detail the results of the energy model work. Finally, section 4 is the conclusion of the analysis, and it proposes further research subjects. 2. Literature review In order to choose a suitable modelling tool, energy system models and studies in the literature were reviewed. In the litera- ture, 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., MAR- KAL/TIMES, MESSAGE, LEAP, etc.), equilibrium (e.g., MARKAL, PRIMES, etc.), top-down (ENPEP-BALANCE, LEAP, etc.), bottom-up (HOMER, RAMSES, MARKAL/TIMES, MESSAGE, etc.), operation optimization (BALMOREL, MESSAGE, RAMSES, etc.), and invest- ment optimization tools (MESSAGE, MARKAL/TIMES, RETScreen, etc.) as categorized in Ref. [30,31]. In Table 1, some energy modelling studies obtained from liter- ature in the last years were listed. Depending on the research objective, modelling can be done for all energy, just electricity, only demand or just one energy sector such as industry. As presented in the table, both developed (UK, Ireland, Taiwan) [32e34] and developing countries (Greece, Iran, Turkey, Ethiopia, Bangladesh, Pakistan, Indonesia, Colombia etc.) [30,35e40] were studied as a case study. In the last years, besides several LEAP studies, models which utilized TIMES, MARKAL, MESSAGE and some developed optimization models also exist in the literature. For instance, Amirnekooei et al. worked on several demand and supply-side management strategies including the utilization of electric stoves in place of natural gas-fuelled stoves, employment of coal power plants the utilization of hydro-pump storage and integrating gas turbine plants to combined-cycle ones for Iran by using LEAP. The results showed the natural gas and crude oil savings while considering these strategies in Iran [35]. Roinioti et al. studied Greece all energy system and developed scenarios by considering the different target of emission reduction and economic growth. The study presented that scenarios with high renewable energy penetration decrease CO2 emissions while the capital cost is increasing [41]. Tsai and Chang investigated emission mitigation measures of Taiwan by 2030. The study included both technologies and tax measures. All sectors in Taiwan require to decrease energy intensities below the BAU scenario by 48å3% to meet its carbon reduction targets for 2050 [33]. Nieves et al. worked on demand and emission forecasting by considering the main energy sectors (industry, housing, and transport). Each sector studied separately based on scenarios including low-high economic growth and po- tential incentives for new technologies [39]. On the other hand, although any scientific study related to all energy sector modelling for Chile does not exist in the literature so far, there are some recently published studies related to power generation and electricity expansion planning for Chile [22e29]. Most of these studies are developed based on optimization models. For

instance, Quiroga et al. worked on projections of the Chilean electric system's expansion without and with taxes, and demand growth estimation. The results showed that the availability of renewable energy capacity could improve the effectiveness of pollutant taxes. Verastegui et al. studied the Chilean power system expansion by 2040 by considering the government's decarbon- ization plan. The research showed interesting results of the gen- eration portfolio based on phasing out coal power plants by 2030, 2035 or 2040 [29]. O'Ryan et al. investigated renewable energy penetration on power expansion planning in Chile. CO_2 emissions of developed scenarios are obtained 10e15% less than business as usual scenario due to the significant share of renewables in the energy portfolio of developed scenarios [28]. In this study, LEAP was chosen as a modelling tool. LEAP is a software, developed by the Stockholm Environment Institute, Boston, to analyze energy demand and supply, energy policy, resource extraction, and accounting GHGs emissions [42]. LEAP has following advantages: permitting scenario analysis in terms of energy, environment and economy, having ability to follow energy consumption, production and resource extraction in all sectors, requiring less initial data input, providing a Technology and Envi- ronmental Database (TED) which offers up-to-date energy tech- nologies data from a wide range of sources, affording data visualization for end-users [31], and finally being free of charge for academics and PhD students. Table 1 Some energy modelling studies in the literature. Scenario approach Sector Country Model Reference Renewable energy penetration in Crete's electric system Resource planning integration Scenarios including uncertain aspects and technology options for clean energy usage Climate mitigation and global warming minimization potential Sustainable energy scenario options to meet the challenges of both energy security and means of climate change mitigation Energy efficiency and CO_2 mitigation potential in the industry sector The impact of renewable energy, energy conservation and efficient technologies Renewables for energy security and carbon mitigation Electricity Energy Energy Electricity Energy Energy in Industry sector Electricity Electricity Moderate energy access, accelerate energy access policies, renewable energies promotion and energy Energy (Demand) efficiency policies Renewable Energy Potential for Thailand's NDC Energy (Demand) Policy analysis including renewable energy clean coal, energy efficiency and conservation Electricity Reduction targets for greenhouse gas emissions for 2020 and 2050 Energy Climate and energy scenarios for 2050 Energy Scenarios with different policies: CO_2 emission reduction constraint, renewable energy production Electricity targets etc. Low carbon development roadmap Energy Emission reduction scenarios Energy Energy technology options under different scenarios Electricity Energy mix and nuclear option in Malaysia taking into account the national energy policies Energy (Demand) Energy supply strategies by considering minimized the total system costs Energy (Supply) New energy strategies introduced by the government including the nuclear power plant, hydropower Electricity and renewable energy Scenarios with the lowest cost of generation and the lowest CO_2 emissions Electricity Power system expansion planning under global and local emission mitigation policies Electricity Analyzing the energy demand and greenhouse gas emissions Energy Greece Iran Greece Panama Ethiopia Turkey Bangladesh Indonesia and Thailand Africa Thailand Pakistan Ireland Ireland United Arab Emirates Taiwan UK India Malaysia Syria Malaysia Indonesia Chile Colombia LEAP LEAP LEAP LEAP LEAP LEAP LEAP LEAP LEAP LEAP LEAP TIMES TIMES MARKAL MARKAL MARKAL MESSAGE MESSAGE MESSAGE MESSAGE Optimization Model Optimization model LEAP [43] [35] [41] [44] [36] [45] [37] [46] [30] [47] [38] [48] [32] [49] [33] [34] [50] [51] [52] [53] [40] [24] [39] 3. Methodology The methodological approach in this research is mainly based on a literature review, scenario description, scenario quantification, verification of model reliability, results and comparison, as illus- trated in Fig. 1. The literature review is explained in the previous

section in order to give more information about energy modelling researches in the literature and energy/electricity studies about Chile. The following steps of the methodology are explained in additional detail within the following sections. 3.1. Scenario description The main step of the methodology is the scenario description in which each scenario was determined based on reviewed informa- tion. At this stage, current policy, current NDC, updated NDC, and decarbonization plans of Chile were reviewed from published in- ternational and government reports and these strategies were added to the scenarios. Additionally, the energy requirement to meet energy-related Sustainable Development Goals was investi- gated to make a further scenario in the model to compare to other scenarios. Finally, six different scenarios were determined as fol- lows and the comparison of scenarios can be seen in Table 2: Reference Scenario (Ref): This scenario takes into account the shift in the energy sector between 2008 and 2015 and calculates the energy sector estimates for 2030 according to this trend. It also ignores current policy, new policy, international and national promises by 2030. Nationally Determined Contributions (NDCs) Scenario: This scenario considers some actions and targets of NDCs of Chile, which was presented to the United Nations Framework Convention on Climate Change in 2015 [3,11]. This scenario considers 30% emission reduction by 2030, reduction of projected energy consumption, electricity demand growth for the transportation sector, renewable energy promotion, energy efficiency and no decarbonization as presented in Table 2. New NDCs Scenario: In October 2019, Chile proposed an upda- ted NDCs based on the previous promises. This scenario takes into account renewed NDCs which includes a 45% reduction in GHG when it is compared to 2016 [54]. In order to have considerable emission reduction, besides NDC, efficient usage of energy, biomass usage restriction in the residential sector, and significant energy demand reduction were considered in this scenario. Current Policy Scenario: This scenario considers the last energy plan of the former government (Energy 2050) and the first energy plan of the new government of Chile (Route 2018e2022) [55,56]. Based on these plans, 30% emission reduction, 30% energy demand reduction in the residential sector, energy efficiency in major sec- tors, fossil fuels replacement with electricity, 57% electricity gen- eration from renewable energy by 2030, fast improvement on transmission and distribution (T&D) lines, and restriction on biomass usage in the residential sector were considered. Current Policy þ Decarbonization Scenario: The government decided to start the process of decarbonization of the energy matrix through the preparation of a timetable for the withdrawal or reconversion of coal-fired plants. According to the decarbonization plan, all coal power plants will be phased out by 2040. Therefore, in this scenario, besides all requirements of the current policy, the new decarbonization plan of government which takes into account phasing out 1047 MW coal power plants by 2024 is also considered [55e57] and also additional coal phase-out in which coal power plant capacity is reduced to 2500 MW by 2030 is considered. SDGs Scenario: Based on our previous study, Chile requires approximately 16,048,414.24 Gigajoules additional energy to meet energy-related SDGs, which increase energy demand by 2030. This scenario takes into account all current policies, decarbonization and also additional demand to meet energy-related Sustainable Development Goals (SDGs) by 2030. This extra energy demand impacts other industry, residential and commercial sectors as explained in Appendix A (Table A1). 3.2. Scenario quantification Scenario quantification was performed as the third step of the methodology by generating an energy model by using LEAP for the Chilean energy sector. The developed LEAP model for Chile includes Fig. 1. Flowchart of the methodological approach. Table 2 The summary of scenario description Reference NDCs Scenario [58] New NDCs Scenario [54] Current Policy Scenario Scenario [55,56] Current Policy þ SDGs Scenario Decarbonization Scenario [55e57] Emission reduction No

emission "It is a control mechanism reduction is to check if the scenario considered. is meeting emission reduction." Change in demand "It refers to the demand changing in the scenario based on determined targets due to the energy efficiency of electricity or energy demand. " Not considered 30% emission 45% emission reduction 30% emission 30% emission reduction 30% emission reduction reduction by 2030 by 2030 compared to reduction by 2030 by 2030 compared to by 2030 compared to compared to 2007. 2016. compared to 2007. 2007. (with international 2007. (with international (with international (with international support 35-45% support 35-45% support 35-45% support 35-45% reduction). reduction). reduction). reduction). 20% reduction of Total 38.5% reduction of Energy demand Energy demand change in Energy demand change in projected energy projected energy change in this this scenario comes from this scenario comes from - consumption (total consumption (total scenario comes from a 30% reduction from The additional energy demand) by 2025. demand) by 2030. 30% reduction from residential demand by requirement to meet This reduction is This scenario includes residential demand 2022 and other sectors energy-related SDGs. realized by energy demand decrease by 2022 and other energy efficiency. - 30% reduction from considering the of NDC scenario and sectors energy Also, efficient usage of residential demand by reduction in the additional energy efficiency. energy in major sectors 2022. following sectors and demand reductions from Also, efficient usage are considered as NDC - Also, efficient usage of 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 each sector to meet emission target as follows: Residential: 15% P&C: 15% Mining: 15% Other Industry: 15% Transport: 20% 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 scenario. energy in major sectors This reduction is realized are considered. by considering the This reduction is realized reduction in the following by considering the sectors and fuels: reduction in the following - Residential: kerosene, sectors and fuels: LPG, electricity, natural - Residential: kerosene, gas, biomass share LPG, electricity, natural - P&C: electricity share gas, biomass share - Mining: electricity and - P&C: electricity share diesel share - Mining: electricity share - Other Industry: diesel, - Other Industry: diesel, electricity and biomass electricity and biomass share share -Transport: Diesel and -Transport: Diesel and gasoline share gasoline share - Mining: electricity and diesel share - Other Industry: diesel, electricity and biomass share -Transport: Diesel and gasoline share Transportation Not considered 1.2% electricity 1.2% electricity demand 1.2% electricity 1.2% electricity demand 1.2% electricity demand "It considers any change in demand increase per increase per year is demand increase per increase per year is increase per year is the transport sector due to electricity demand for EV or fossil fuel phase-out targets." year is considered for considered for the the transportation transportation sector sector [59]. [59]. Also, fossil fuels share Also, fossil fuels share year is considered for the transportation sector [59]. considered for the considered for the transportation sector [59]. transportation sector [59]. Also, fossil fuels share Also, fossil fuels share (diesel and gasoline (diesel and gasoline (diesel and gasoline (diesel and gasoline Also, fossil fuels share) was decreased due share) is decreased due to share) is decreased share) is decreased due share (diesel and due to the increase of to the increase of gasoline share) is to the increase in the increase in electricity electricity share. share. electricity share. electricity share. decreased due to the increase in electricity share. Capacity and Generation Real installed Real installed Real installed capacity Real installed Real installed capacity Real installed capacity Mix capacity and capacity and and generation values capacity and and generation

values and generation values "It shows the change in generation generation values were entered into the generation values were entered into the were entered into the the current electricity values were were entered into the LEAP until 2018. were entered into LEAP until 2018. LEAP until 2018. share portfolio by entered to the LEAP until 2018. Also, government's the LEAP until 2018. Also, government's Also, government's decreasing or LEAP until 2018. Also, government's capacity expansion plan Also, government's capacity expansion plan is capacity expansion plan is increasing the current Also, the capacity expansion is added to the scenario capacity expansion added to the scenario added to the scenario installed capacity." capacity plan is added to the until 2024. Finally, the plan is added to the until 2024. until 2024. between 2018 scenario until 2024. capacity remained the scenario until 2024. Moreover, additional Moreover, additional and 2030 is Finally, the capacity same between 2024- Moreover, capacities are added for capacities are added for increased based remained the same 2030. additional capacities solar PV, solar CSP, wind solar PV, solar CSP, wind on the between 2024-2030. 20% of the energy matrix are added for solar and hydro between 2024- and hydro between 2024- compound 20% of the energy in the generation is PV, solar CSP, wind 2030. 2030. annual growth matrix in the made up of and hydro between 57% of electricity 57% of electricity rate (CAGR). generation is made unconventional 2024-2030. generation from generation from up of unconventional renewable energies by 57% of electricity renewable energy by renewable energy by renewable energies 2025. generation from 2030. 2030. by 2025. renewable energy by At least 50% of the fuels in At least 50% of the fuels in 2030. the energy matrix should the energy matrix should At least 50% of the be low in GHG emissions be low in GHG emissions fuels in the energy and atmospheric and atmospheric (continued on next page) Table 2 (continued) Reference NDCs Scenario [58] New NDCs Scenario [54] Current Policy Current Policy þ SDGs Scenario Scenario Scenario [55,56] Decarbonization Scenario [55e57] Transmission and Distribution (T&D) Losses matrix should be low in GHG emissions and atmospheric pollutants. pollutants. Decarbonization is realized based on governments plan by 2024 and an additional plan is considered by 2030 [29,57]. pollutants. Decarbonization is realized based on governments plan by 2024 and an additional plan is considered by 2030 [29,57]. Improvement in T&D losses are T&D losses are considered 4.5% by not considered 2030 (Moderate considered 4.5% by 2030 considered, and the considered, and the losses considered, and the losses (Moderate improvement losses reached 3.8% reached 3.8% by 2030 reached 3.8% by 2030 T&D losses are Historical growth is Historical growth is Historical growth is improvement on T&D on T&D lines) by 2030 (Fast (Fast improvement on (Fast improvement on lines) improvement on T&D lines) T&D lines) T&D lines) Fossil fuel No fossil fuel Additional coal Additional coal phase- Additional coal 1047 MW coal power 1047 MW coal power transformation transformation phase-out is not out is not considered in phase-out is not plant capacity is phased plant capacity is phased "It addresses changing the is considered considered in this this scenario. considered in this out until 2024 (planned out until 2024 (planned total share of fossil fuel scenario. scenario. by the government) and by the government) and power plants in the also additional coal phase also additional coal phase current net generation. out is considered by 2030. out is considered by 2030. It can be executed by Thus, total coal capacity is Thus, total coal capacity is decommissioning the reduced to 2500 MW by reduced to 2500 MW by fossil fuel power plants 2030. 2030. installed capacity or Natural gas/diesel Natural gas/diesel using more clean fuels." remained at the same remained at the same capacity. capacity. Energy Efficiency (EE) EE is not EE is considered for 2020 EE action plan 2020 EE action plan 2020 EE action plan target 2020 EE action plan target considered all sectors. target is considered [60]. target is considered is considered [60]. is considered [60]. Biomass usage was Biomass usage

was [60]. Biomass usage was Biomass usage was restricted in the restricted in the Biomass usage was restricted in the restricted in the residential sector. residential sector. restricted in the residential and other residential and other residential and other industry sector industry sector industry sector. historical energy sector data from 2008 to 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 <u>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</u> [19,61]. <u>Thus, the</u> mining sector was analyzed in the model separately from other industry sectors. The defined scenarios from the previous step were quantified and implemented to the developed energy model. Fig. 2 shows the structure of the LEAP model. LEAP requires demographic (population) and macroeconomic (GDP, sectoral GDP) data for the baseline of the model [42]. These data are used as in- puts for demand analysis. Also, activity levels and energy intensity of each sector are required for demand analysis. In this study, ac- tivity level and energy intensities are assumed as listed in Table 3. The population was assumed as activity level for residential, public and commercial sectors when sectoral GDP shares were accepted as activity level for mining, industry and transportation sectors. Also, auto consumption and non-energy sectors mentioned in the energy balance were quantified with their total energy values in the model. Besides key assumptions such as demographics and macroeco- nomic data, LEAP requires historical energy demand and trans- formation data to forecast future values. Transformation analysis follows demand analysis as shown in Fig. 2. It includes electricity generation, transmission and distribution losses of the system. For transformation analysis, technical parameters such as lifetime, ef- ficiency, availability and cost values of power plants are required. The model is also suitable for emission analysis. LEAP allows generating several scenarios with the created model and compares the results based on energy and environmental outputs. The equations considered in the LEAP model for energy demand, net energy consumption for transformation, carbon emissions from final energy consumption, and carbon emission from energy transformation are presented as follows [30,31,42]. Energy demand is a function of activity level and energy in- tensity for each sector, and it is calculated as Eq (1):

$$ED_{b,s,t} = TA_{b,s,t} \cdot EI_{b,s,t} \quad (1)$$

ED: energy demand (GJ) TA: total activity (person or US$) EI: energy intensity (GJ/person or GJ/US$) Also, b is the branch, s is the scenario, and t is the year. Additionally, the net energy consumption for transformation is calculated as Eq (2):

$$ET = \sum_{p} ETP_{sec,tec} \cdot \left(\frac{1}{f_{p,sec \cdot tec}} - 1 \right) \quad (2)$$

ET: net consumption for transformation (energy loss for a transformation process) (GWh) ETP: product from the transformation process (GWh) Also, f is energy transformation efficiency, tec is the technology, p is the type of primary energy, and sec is the type of secondary energy. Moreover, the carbon emissions from final energy consumption are calculated from Eq (3):

Fig. 2. The structure of LEAP calculations [42].

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

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

$$CE_{p,s,t} = TA_{b,s,t} \cdot EI_{b,s,t} \cdot EF_{b,s,t} \quad (3)$$

CE: carbon emissions (MMetric Tonnes CO2 eq) EFb,s, t: carbon emissions factor from the sector or branch b, scenario s and year t. Finally, the emissions from energy transformation are calculated in LEAP as shown in equation (4):

$$CET =$$

$$ET_{P_{sec,tec}} * f_{p,sec,tec} \cdot 1 * EF_{p,sec,tec} \quad (4)$$

CET: the carbon emission (MMetric Tonnes CO2 eq) EFp, sec, tec: the emission factor from one unit of primary fuel type p, used to produce the secondary fuel type sec through the technology tec. Relevant quantitative and qualitative information for modelling were gathered via scientific databases (Science Direct and Research Gate), open-access search engines (Google and Google Scholar), open access international organization reports, and publicly avail- able Chilean governments' reports. For instance, national energy balances are reported annually on the website of the National Energy Commission of Chile [62]. Demographic data are obtained from the National Statistics Institutes of Chile and the World Bank Group [63,64]. Macroeconomic data are taken from international statistic websites, Chilean government report and ministries pub- licly available documents [65e67]. Moreover, the required data for the transformation part of the model, such as power plant installed capacities and historical generation, are acquired from the reports and website of the National Energy Commission of Chile [68]. Technology and power plant information such as availability, effi- ciency are taken from published peer-reviewed articles, LEAP database, and international thesis [42,69,70]. Finally, emission impact data is taken from the available database in the LEAP model: Technology and Environmental Database [42]. To create a model in LEAP, users need to follow the basic structure and initial data sets explained as above. Required initial data (demographic, macroeconomic and energy balance data) can be obtained from national governmental and international in- stitutions. This basic structure makes the model easier for repro- ducibility and replicability, and it enables the adoption of the LEAP model in various countries. After quantifying all defined scenarios, the results including energy demand and supply, emissions for each scenario were compared, and the detailed results were given in the following section.

4. Results and discussion

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

4.1. Reliability check for the energy model

Before presenting the results, the approach to check the accu- racy of the model is also explained in this section. In order to verify the reliability of the created energy model, energy/electricity de- mand projections for 2030, and CO2 emission values for base case are compared to published government reports and United Nations Framework Convention on Climate Change (UNFCCC) country emission reports. Table 4 presents CO2 emission (without LULUCF/LUCF) values obtained from UNFCCC and LEAP results for base years. In LEAP Chile model, 2015 is assumed as the base year of the model. And the first calculations are realized for the year 2016. In order to check the reliability of the model, emission values between 2010 and 2015 are calculated based on Technology and Environmental Database (TED) of LEAP and the difference between the real (UNFCCC values) [71] and calculated values (LEAP result) are presented in the table. LEAP results showed higher emission values with 3e5.5% error margin between 2010 and 2013. On the contrary, LEAP values are obtained lower than UNFCCC values with a 1.5e2.2% error margin for 2014 and 2015. Additionally, energy and electricity demand values are compared for LEAP reference scenario results and government's national energy balances, as presented in Table 5. As mentioned above, 2015 is assumed as the base year and the model calculates the demand results for 2016 and beyond, that allows comparing real and calculated values. Reference scenario energy demand is

Table 4 CO2 emissions (without LULUCF/LUCF) values obtained from UNFCCC and LEAP results for base case (MMetric Tonnes CO 2).

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

obtained higher values than the values in 2016e2017 Chilean Na- tional Energy balances [15,72] with

0.23% and 0.27% error margin, accordingly. Also, the calculated energy demand (LEAP reference scenario result) for 2030 is compared to government energy projection. Depending on the low, medium and high demand projection, the report indicated that energy demand for 2030 would vary between 350,000e400,000 Tcal [12]. When the low energy demand pro- jection of government for 2030 is compared to LEAP result, ? 1.50% error margin is obtained for the calculated value. Finally, the pro- jected 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 100,000e115,000 GWh depending on low, medium and high electricity demand scenarios [12]. When low electricity demand projection of government is compared to the calculated value, LEAP results showed lower demand value for electricity with a ?4.61% error margin for 2030. 4.2. Comparison of scenarios Fig. 3 shows the total energy demand projection for all scenarios between 2010 and 2030. Without considering any policy for effi- cient use of energy, total energy demand will reach approximately 1450 million GJ as shown in the reference scenario. Other scenarios showed significant decreases due to having reduction targets on energy demand. NDC scenario is obtained as the second highest energy demand by 2030 although it has a 20% energy saving target by 2025. Due to its major emission reduction target, the new NDC scenario should have at least a 38.5% reduction in energy demand when it is compared to the reference scenario by 2030. Thus, the new NDC policy shows the lowest demand for 2030 which is 887 million GJ when it is compared to other scenarios. Current policy and current policy þ decarbonization scenarios had the same demand value near 980 million GJ. Also, due to its extra energy requirement to meet goals, SDG scenario energy de- mand resulted higher than the current policy scenario and it was obtained approximately 997 million GJ by 2030. Finally, the NDC scenario has 20% reduction target from total demand by 2025 when current policy scenarios have a 30% reduction in the residential sector by 2022 and other sectors. This additional residential de- mand decrease in current policy scenarios results to lower total energy demand when it is compared to the NDC scenario. In Chile, the reduction in energy demand depends on energy efficiency policies and measures as mentioned in Government's action plans explicitly [56,60]. According to the energy efficiency action plan, the Chilean government set the goal of reducing Chile's projected 2020 energy demand by 12% via energy efficiency pro- grams by 2020 [60]. When the results of energy demand reduction were checked for each scenario, current policies and SDG scenarios showed reductions of 13.6% and 13.0%, accordingly when new NDC achieved 17.6% less demand than projected energy demand value for 2020. Moreover, the results showed that NDC demand reduction was obtained 10.8% less than projected value in 2020, which means that although new NDC, current policy and SDG scenarios met the target of 12% demand reduction by 2020 based on energy efficiency plan of the Chilean government, NDC scenario could not reach the target for 2020. If energy efficiency measures are well defined and planned based on energy sectors, energy demand reduction will still be realistic as occurred successfully in Denmark, Finland and Switzerland [73]. However, that kind of policies may require enough financial support internationally (as mentioned in NDC) and state budgets. Since the reduction is planned by the country, it should be ready financially. Fig. 4 presents the sectoral energy demand for each scenario in 2030 and base year 2015. The main results showed that Table 5 Energy and electricity demand comparison for real and calculated values. Year Energy Demand (Tcal) LEAP energy demand results (Tcal) Error (%) Electricity Demand (GWh) LEAP Electricity Demand (GWh) Error (%) 2016 284,778 [15] 285,430 0.23% e e e 2017 288,901 [72] 289,670 0.27% e e e 2030 350,000 (low)-400,000 (high) [12] 344,760 ?1.50% 100,000 (low)-115,000 (high) [12] 95,388 ?4.61% Fig. 3. Total energy demand projection for scenarios. transportation and industry dominated demand in

all scenarios. When the base year 2015 and reference scenario 2030 results are compared, public, commercial, mining and industry sectors showed significant demand increase in 15 years. On the contrary, an increase in residential sector demand resulted vaguely. The demand decline in the residential sector at current policies can be seen clearly due to their specific efficiency targets when compared to the reference scenario and NDC scenarios. Although public, commercial and industry sectors show a declining trend for all scenarios compared to the reference scenario, the SDG scenario requires more energy by 2030 for those sectors in order to meet energy- related goals. Also, mining and other industry sectors have major demand reduction in the new NDC scenario due to its considerable demand decrease in all sectors. The transportation sector, which is predominantly petroleum derivatives, follows a trend towards electric, hybrid, and more efficient vehicles. Although energy efficiency is applied in the transportation sector, it is still the dominant sector in energy consumption when compared with other sectors and its share reached 35% for NDC and new NDC scenarios, and 38% for current policy and SDG scenarios when it is obtained 32% for reference scenarios. Finally, it can be inferred that major energy savings can be achieved when a correct energy efficiency policy is implemented in the energy-intensive sectors of Chile. In Fig. 5, CO_2 emission (Million Metric Tonnes CO_2 Equivalent) of the scenarios are illustrated. As summarised in Table 2, Chile declared 30% emission reduction by 2030 compared to 2007 in its NDC, which can increase up to 35e45% reduction with Fig. 4. Sectoral energy demand for each scenario at 2030. international support. Also, the new NDC scenario has 45% emission reduction target compared to 2016. After applying all strate- gies to each scenario, emissions are decided as a control mechanism to check if the scenario is meeting emission reduction or not. According to United Nations Framework Convention on Climate Change (UNFCCC) reports for Chile, CO_2 emission had the major share which was 74% in 2000 and 81% in 2016 (last reported year) between all greenhouse gas (GHG) emissions [71]. Due to its significant impact, CO_2 emissions are considered and compared in this study. The CO_2 emission (without land use, land-use change and forestry (LULUCF)) value for 2007 and 2016 in Chile were 62.46 and 87.44 million metric tonnes, accordingly [71]. Emission re- ductions compared to 2007 (CO_2 per GDP) for current policy, cur- rent policy þ decarbonization, and NDC scenarios are calculated as 60.0%, 60.7%, and 51.8, respectively, which means that these sce- narios are meeting at least 30% emission reduction target compared to 2007 value (CO_2 per GDP) in the scenario descriptions. Also, new NDC and SDG scenarios have a 52.9% emission reduction when they are compared to 2016 value, that means they are also meeting their defined targets. Also, the important point is that the emission reduction difference between current policy and current policy þ decarbonization results from the extra phased out coal power plants in the decarbonization scenario. Finally, it is interesting to mention that current policy and current policy þ decarbonization scenarios also meet a 45% emission reduction target when compared to 2016 value, and they had 53.2% and 54.0% emission reduction, respectively. However, the NDC scenario only reduces 43.5% of total emissions compared to the 2016 values. Although most of the scenarios meet the emission targets for 2030, it is important to analyze the contribution of sectoral emis- sions. Fig. 6 shows how many total emissions come from demand and transformation. Although the energy transformation sector contributes seriously to emission generation and policies have al- ways 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 emis- sions in Chile tend to come from demand sectors. Almost 40% of total emissions come from the transformation (electricity genera- tion) in 2015. Although emissions from the transformation sector show a significant reduction in different scenarios, the decrease in demand-side is observed slightly.

However, due to its additional energy demand reductions from each sector to meet emission target (residential: 15%, P&C: 15%, mining: 15%, other industry: 15% and transport: 20%), new NDC scenario resulted in less contribution to CO2 emissions in the demand side, which means demand-side policies in the new NDC scenario proved to be more successful in reducing emissions. Also, when the contributions of main sectors in demand-side to CO2 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. There- fore, in addition to implementing decarbonization policies to reduce emissions from the transformation sector (mainly electricity production), appropriate energy efficiency and renewable energy policies should be developed and implemented for demand sides of transport, mining and other industries in Chile. In addition to the sectoral emission contribution, it is important to analyze emissions by fuel for each scenario. Fig. 7 presents demand-side CO2 emission comparison of scenarios by fuels by 2030 and base year 2015. The reference scenario has the highest demand-side emission production, which is followed by the NDC scenario when new NDC has the lowest value near 40 million metric tonnes of CO2 emissions. Due to having similar sectoral energy demand, current policy, current policy þ decarbonization and SDG scenarios had the same emission results for demand-side near 50 million metric tonnes of CO2. Diesel has the main contri- bution to emissions, and it is followed by gasoline, natural gas, LPG, jet kerosene, and oil. The emissions of diesel, jet kerosene and gasoline mainly come from the transport sector. Diesel usage of mining also has a direct contribution to emissions of the demand side. Also, the other industry sector has major consumption of oil, diesel, natural gas, LPG, and coal which contributes emissions. Besides the demand-side CO2 emission comparison of scenarios by fuels, the results of transformation side CO2 emission compari- son by fuels by 2030 are presented in Fig. 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 þ decarbonization and SDG scenarios showed essential emission reduction in the transformation side due to implemented significant renewable energy generation pri- ority to the model for these scenarios. Although emissions from coal are mostly dominant for each scenario, current Fig. 5. CO2 emission without LULUCF (MMetric Tonnes of CO2). Fig. 6. Emission comparison for scenarios by demand and transformation in 2030. Fig. 7. Demand-side CO2 emission comparison of scenarios by fuels by 2030. policy þ 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 CO2) between current policy and current policy þ decarbonization scenarios come from the phased-out coal power plants in the decarbonization scenario by 2030. Fig. 9 shows the capacity projection for each scenario between 2010 and 2030. The reference scenario has only biomass, coal, diesel, gas, solar PV, hydro, wind and cogeneration power plants. Real installed capacity values were entered into the LEAP until 2018 for all scenarios. Also, the capacity between 2018 and 2030 is increased based on the compound annual growth rate (CAGR) for the reference sce- nario, 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 þ decarbonization and SDG scenarios include coal phase-out in the model. The Chilean gov- ernment has planned to phase out 1047 MW of coal power plant capacity by 2024 and to get rid of all coal power plant by 2040. In addition to the plan by 2024, total coal capacity in current policy þ decarbonization and

SDG scenarios is reduced to 2500 MW by 2030. For the decarbonization plan, natural gas and diesel capacities remained the same due to not having any phase- out plans for these fuels by the government. Also, it is assumed to use available diesel capacity as back up when necessary, not as the main production. However, if also natural gas phase-out contributes to the decarbonization plan, coal capacity reduction can be smoother than current policy þ decarbonization scenario which has approximately 2500 MW reduction since 2018. NDC and new NDC scenarios have a moderate increase in capacity of solar PV, wind and hydropower plants by 2024 as government plan [68] and Fig. 8. Transformation side CO2 emission comparison of scenarios by fuels by 2030. Fig. 9. The capacity projection for each scenario between 2010 and 2030. until 2030 the capacities remained the same. However, in current policy, current policy þ decarbonization, and SDG scenarios, ca- pacity 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/tCO2 for fixed turbines or boilers above 50 MWth in Chile [24,29]. Besides emission targets, renewable electricity generation per- centage is mentioned in the scenarios as another target to compare. Fig. 10 presents generation percentages by fuel and renewable energy share for each scenario in 2030. In order to maintain the balance between consumption and production in terms of power plant operations, base power plants have essential importance. Decommissioning of base power plants with high capacity such as coal and gas power plants may cause partial imbalances in the system in terms of supply reliability. For this reason, natural gas and a small amount of coal power plants are considered as base plants considering these imbalances in the establishment of scenarios. Also, among the renewable energy sources, geothermal and hydropower plants are generally considered as base power plants. Accordingly, the contribution of hydropower plants to production as a base plant has been prioritized in the generated scenarios. In 2015, electricity was mostly generated from coal, hydro and gas power plants and renewable generation share was 38%. The model results showed that the reference scenario has a similar fuel combination as the base year which is mostly fossil fuels, and renewable energy generation share is obtained 47% with the contribution of more solar PV and wind power production. In NDC and new NDC scenarios, electricity generation from fuels reduced to almost 40%, which met the scenario target "20% of the energy matrix in the generation is made up of unconventional renewable Fig. 10. Generation percentage by fuel and renewable energy share for each scenario at 2030. energies by 2025". Additionally, the current policy has the target of having 60% renewable electricity generation by 2035 [10,56]. When the target by 2030 is considered, it will be approximately 57e58% renewable electricity generation. As shown in the figure, current policy, current policy þ decarbonization and SDG scenarios reached more than 80% renewable electricity generation by 2030 with or without decarbonization. In current policy and decarbonization scenarios, electricity generation is supplied from various resources and mostly renewable energies such as 28% wind, 25% solar PV, 17% hydro and, 13% solar CSP. Diversity in production, production from the country's national resources and self-sufficiency are crucial elements to increase energy reliability and reduce external dependence in Chile. When the current policy þ decarbonizacion scenario is compared to the reference scenario, the production of decom- missioned coal power plants is replaced with renewable energy (solar and wind) sources. Also, wind, PV solar, CSP solar and hy- dropower plants become more dominant and the main elements of electricity generation for current policy, current policy þ 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 emis- sions and more diversification in terms of energy production. Finally, the methodology

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

5. Conclusion and policy implications

The aim of this study is creating a model to forecast energy demand and supply for Chile considering different policies by 2030, analyzing the impact of different policies (current policies, na- tionally determined contributions, sustainable development goals) and decarbonization on energy planning in Chile by 2030, and evaluating the determined scenarios if they meet the defined tar- gets. This work contributes to the literature by developing a long-term energy plan including all sectors for Chile, describing energy scenario alternatives and analyzing national/international com- mitments such as nationally determined contributions and sustainable development goals. The main findings of the study are as follows: due to its signif- icant emission reduction target, the new NDC scenario has at least a 38.5% reduction in energy demand when it is compared to the reference scenario by 2030. Current policy and current policy þ decarbonization scenarios had the same demand value near 980 million GJ. Also, due to its extra energy requirement to meet goals, SDG scenario energy demand resulted higher than the current policy scenario. NDC scenario has 20% of total energy de- mand reduction when the current policy has a 30% specific reduction in the residential sector and other main sectors as in NDC scenario. This additional residential demand decrease in current policy scenarios results in 6% lower total energy demand than the NDC scenario. Denmark, Switzerland and Finland showed an achievement on decoupling of economic growth from energy use, which means that economy is still growing while energy demand growth does not increase. After 2013, the similar tendency is observed in Chile. For instance, energy use per capita decreased by 7.68% in 2014 and 8.93% in 2015, which means that GDP per capita was increasing while energy use per capita showed decreases after 2013 [73]. Therefore, when considering EU countries successful stories, international support and energy demand reduction trend of Chile after 2013, these reductions seem reasonable. Emission decline for current policy, current policy þ 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 sce- narios have a 52.9% emission reduction when they are compared to 2016 value, which means they are also meeting the 45% emission reduction target by 2030. However, NDC scenario did not achieve 45% emission reduction target by 2030. Although the energy transformation sector contributes to emissions significantly and policies have mostly been implemented to reduce emissions in the transformation sector, the demand sector has a major contribution to the emissions in Chile when it is compared to the transformation sector. The results showed that even though emissions from the transformation sector demon- strate a significant reduction by 2030 in different scenarios, the decrease in demand side is not clearly noticed. The reference sce- nario has the highest demand-side emission production when NDC, new NDC, current policy, current policy þ decarbonization and SDG scenarios showed essential emission reduction in the trans- formation 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) be- tween current policy and current policy þ decarbonization sce- narios comes from the phased-out coal power plants in the decarbonization scenario by 2030. Current policy, current policy þ decarbonization and SDG sce- narios achieved more than 80% renewable electricity generation by 2030 with or without decarbonization. In current policy þ decarbonization scenarios,

electricity generation is sup- plied 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 de- pendency in Chile. When the current policy þ 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 hy- draulic power plants become major plants of electricity generation for current policy, current policy þ decarbonizacion, and SDG scenarios. To summarise, the following should be considered by policy makers in Chile: a cleaner production portfolio can be created with small amounts of fossil resources (gas or coal) and hydro as base power plants, and with more renewables, which results in less emissions and more diversification in terms of energy production. Chile requires appropriate energy efficiency and renewable energy policies (with international support) to be implemented for de- mand sides of transport, mining, and industry sectors to reduce significant emissions at demand-side as it has decarbonization plan for transformation side. Finally, this study has some limitation due to the nature of the research methods applied and unavailable information. The study focuses on secondary data collection and literature reviews. All the analyses are shaped by the conditions of the country studied. This modelling approach is potentially limiting because it provides re- sults for all Chilean energy sector, not regional analysis. Also, this study does not consider the sub-sectors of energy sectors in Chile and not having publicly available complete data sets. CO_2 emission without LULUCF is taken into account. Another limitation is weather impacts on electricity generation. In this study, LEAP could not consider weather impacts on renewable energy power plants such as hydroelectric, solar and wind. The current LEAP's technol- ogy and emissions databases are also quite limited in scope. There are some interesting research areas as future studies in energy modelling, and they are mentioned as follows: developing an energy model for Chile which analyze the different regions separately (SEN, SEA, SEM), realizing sensitivity analysis on devel- oped scenarios, and adding to the model other technologies (such as battery storage system) not widely available today but that could play an important role in the future, to see their impact on the energy system in Chile.

CRediT authorship contribution statement Yeliz Simsek: Conceptualization, Validation, Formal analysis, Investigation, Resources, Software, Data curation, Writing - original draft, Visualization. Hasret Sahin: Formal analysis, Investigation, Resources, Software, Data curation, Validation. Alvaro Lorca: Writing - review & editing, Validation, Supervision. Wayan G. Santika: Conceptualization, Data curation, Writing - original draft, Visualization. Tania Urmee: Conceptualization, Methodology, Writing - review & editing, Supervision. Rodrigo Escobar: Writing - review & editing, Validation, Supervision.

Appendix A Table A1 ENERGY-RELATED SDGs Indicator assessment for Chile 2030: Energy Intensity (EI): Energy requirement/savings to meet the target for Chile: Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture Target Indicator 2.1.1: Prevalence of Data: 2000e2016 [74] Assumptions: Total energy is calculated to 2.1 undernourishment CAGR: ?1.20% EI ¼ DfECf=ðEonfarm þ EofffarmÞ Df ¼ Country's depth of food nourish all people by 2030 and EI (max) is Prevalence of undernourishment in 2030: deficit ¼ 90.25 kcal*person?1*day?1 considered. 498,875.60 people [75] E_required_total ¼ ECf ¼ The food energy content of 265,057.83 GJ cooked potato ¼ 930.00 kcal/kg [76] This extra demand will impact other Eonfarm, max ¼ On-farm agriculture industry sector due to including energy usage ¼ 0.005 GJ/kg [77] agriculture. Eofffarm, max ¼ Off-farm

agriculture energy usage ¼ 0.010 GJ/kg [77] EI (max) ¼ 0.531 GJ/cap/year Goal 5. Achieve gender equality and empower all women and girls Target Indicator 5.b.1: Proportion of 5.b individuals who own a mobile telephone Data ¼ 2016e2020 [78] CAGR ¼ 1.18% Population without a mobile phone in 2030 ¼ 5,130,570.70 people EI for owning a mobile phone [75,79]: The total energy requirement when all EI ¼ Eb/th ¼ ((16 kj/phone)/(27 h)) * (24 h/day) * (1 phone/person) Eb ¼ 1.2 Ah (about 16 kJ) per phone population own a mobile phone by 2030: E_required_total ¼ 26,627.66 GJ This additional demand will increase th ¼ 27 h electricity demand in the residential sector. The energy intensity requirement for a mobile phone is estimated at 0.00519 GJ*cap?1*year?1 Goal 12. Ensure sustainable consumption and production patterns Target Indicator 12.3.1: Global food loss Food losses in Latin America is cited The energy intensity (EI) [75]: E_required_total ¼ 10,263,968.06 GJ 12.3 index approximately 220 kg/cap/year [80]. EI ¼ ðECstoring þ ECretailingÞ*L half It is assumed that this extra demand will The targeted food loss (L_half) will be EC_storing ¼ Energy consumption for impact on electricity use (for storage, 110 kg/cap/year. storing (MJ/kg) Table A1 (continued) ENERGY-RELATED SDGs Indicator assessment for Chile 2030: Energy Intensity (EI): Energy requirement/savings to meet the target for Chile : EC_retailing ¼ Energy consumption for retailing (MJ/kg) L_half ¼ Halving the losses based on target(kg/cap/year) Goal 13. Take urgent action to combat climate change and its impacts Target Indicator 13.1.1: Number of The number of people displaced after the The average embodied final energy 13.1 deaths, missing persons and last three biggest earthquakes and tsunamis intensity to build a temporary, post- directly affected persons in Chile: 1,500,000.00 people in 2010, disaster container house is attributed to disasters per 100,000 970,000.00 people in 2014, and approximately 1.35 GJ*cap?1*year?1 population 1,000,000.00 people in 2015 [81,82]. [75]. The average number of people displaces is obtained approximately 1,156,666.67 people. Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development Target Indicator 17.6.2: Fixed Internet Data ¼ 2010e2017 [83]. The energy intensity to meet the 17.6 broadband subscriptions per 100 CAGR ¼ 7.96% between available years. target: inhabitants, by speed The number of people without subscription 0.284e0.347 GJ/customer [75]. in 2030 ¼ 12,454,704.18 processing, and packaging) of industrial and commercial sectors equally. Thus, the total energy requirement to replace affected people after the disaster in Chile is calculated: E_required_total ¼ 1,565,045.18 GJ The required energy is assumed to impact the construction and industrial sectors. 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 ¼ 3,927,715.51 GJ Telecommunication services belong to the commercial sector and it is assumed that this energy will impact the electricity demand of the commercial sector.

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