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The impact of renewable energy and sector coupling on the pathway towards a sustainable energy system in Chile

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ABSTRACT

The aim of this research is to analyse the impact of renewable energy (RE) technologies and sector coupling via analysing the transition pathways towards a sustainable energy system in Chile. Four energy transition scenarios for the power, heat, transport and desalination sectors were assessed using the LUT Energy System Transition model. The current policy scenario was modelled and compared with three best policy scenarios. The results showed that the transition to a 100 % renewable-based energy system by 2050 is technically feasible. Further, such an energy system would be more cost-efficient than the current policy scenario to reach carbon neutrality by 2050. The results also indicate that Chile could reach carbon neutrality by 2030 and become a negative greenhouse gas emitter country by 2035. In a 100 % renewable-based energy system, solar photovoltaics (PV) would contribute 86 % of electricity generation, which would represent 83 % of the total final energy demand for the year 2050. This would imply the use of about 10 % of the available techno-economic RE potential of the country. Three vital elements (high level of renewable electrification across all sectors, flexibility and RE-based fuel production) and three key enablers (solar PV, interconnection and full sectoral integration) were identified in order to transition to a fully sustainable energy system. Chile could contribute to the global sustainable energy transition and advance to the global post-fossil fuels economy through the clean extraction of key raw materials and RE-based fuels and chemicals production.

1. Introduction

Defossilising the global economy will require radical structural changes [1,2]. This needs to be designed to bring multiple co-benefits to the human-planet system [3,4], and consequently, to the biosphere and to climate resilience [5], as well. In this sense, energy efficiency and

Abbreviations: A-CAES, Adiabatic compressed air energy storage; BEV, Battery electric vehicle; BPS-Un, Best policy scenario unconstraint; BPS-100RE, Best policy scenario 100 % renewable energy; BPS-100RE-HT, Best policy scenario 100 % renewable energy high transmission; BUS, Bus; CAPEX, Capital expenditures; CCS, Carbon capture and storage; CO_2, Carbon dioxide; CL-A, Chile-Aysén; CL-C, Chile-Central; CL-CN, Chile-Central North; CL-M, Chile-Magallanes; CL-N, Chile-North; CL-S, Chile-South; CCGT, Combined cycle gas turbine; CHP, Combined heat and power; C&I, Commercial and Industrial; CSP, Concentrated solar thermal power; m^3, Cubic metre; CPS, Current policy scenario; DAC, CO_2 Direct air capture; DH, District heating; FT, Fischer-Tropsch; FCEV, Fuel cell electric vehicle; FLH, Full load hours; GT, Gas turbine; GW, Gigawatt; GWh, Gigawatt-hour; GHG, Greenhouse gas; HDV, Heavy duty vehicle; HT, High temperature; HVAC, High voltage alternating current; HVDC, High voltage direct current; H_2, Hydrogen; IH, Individual heating; ICE, Internal combustion engine; LUT, LUT University; LCOC, Levelised cost of curtailment; LCOE, Levelised cost of electricity; LCOH, Levelised cost of heat; LCOS, Levelised cost of storage; LCOT, Levelised cost of transmission; LCOW, Levelised cost of water; LDV, Light duty vehicle; LNG, Liquefied natural gas; LH_2, Liquefied hydrogen; LT, Low temperature; MDV, Medium duty vehicle; MT, Medium temperature; MW, Megawatt; MWh, Megawatt-hour; MED, Multi-effect desalination; MSF, Multi-stage flash; OCGT, Open cycle gas turbine; OPEX, Operational expenditures; p-km, Passenger kilometre; PV, Photovoltaics; PHEV, Plug-in hybrid electric vehicle; PP, Power plant; PtH, Power-to-heat; PtX, Power-to-X; PHES, Pumped hydro energy storage; RE, Renewable energy; RO, Reverse osmosis; SF, Solar field; ST, Steam turbine; SNG, Synthetic natural gas; TTW, Tank-to-wheel; TW, Terawatt; TWh, Terawatt-hour; TES, Thermal energy storage; t-km, Tonne kilometre; 2W, Two wheelers; 3W, Three wheelers; €, Euro.

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renewable energy (RE) resources, in combination with electrification of end uses, seem to be vital elements for a successful energy transition, and for instance, in reducing 94 % of energy-related greenhouse gas (GHG) emissions by 2050 [6]. However, the progress made by RE is not fast enough to compete with the rising energy demand so far [7]. According to a recent International Energy Agency report [8], more efforts are needed in key technologies (such us energy storage, hydrogen, smart grids, demand response and direct air capture) towards the integration of energy systems and sustainable fuel production.

1.1. Status of research to design fully sustainable energy systems

Research around the design of 100 % renewable-based energy systems are fairly new, but has received increasing attention in the last decade [9]. Although this kind of research has been carried out at a different scale worldwide, the analysis has often been performed for the power sector and from a technical perspective [9]. In any case, most of the studies conclude that a 100 % RE electric system is technologically feasible [9] and also economically viable [10–12]. Some studies [13–16] at the country level on 100 % RE systems, for all end-use of energy, have revealed that it would be technically possible in the long-term, where electrification, sustainable fuels production and sectoral integration would be pivotal. However, there is still a discussion about the pathways to go down for a fully sustainable energy system.

Table 1 shows a brief overview for selected countries and regions studies that address sustainable energy transition nationally, in different countries, from a database of 550 articles on 100 % renewable energy systems (as of early July 2021) [17]. Articles that only discuss energy transition at global and sub-national level were excluded. Reports on overnight studies were also excluded, because stakeholders and policy-makers are strongly interested in descriptions what measures to be done by when and how the legacy energy system could be used or phased out in a best way. This reflects how to achieve the aim of 100 % renewable energy systems, in several steps over time, starting from the existing reality. In Table 1, only studies that provide pathway descriptions from the present to a 100 % renewable energy system state are considered; where at least the sectors of power, heat, and transportation are included in representing a sector coupled energy system and the PV share in 2050 reaches at least a 50 % contribution in electricity supply for the energy system. This allows an excellent comparison to the results of this research. All identified studies use optimisation models, while OSeMOSYS and its derivative GENeSYS-MOD use time slices of only 6 to 16 data points for a year, while the other models, LUT-ESTM, PyPSA-Eur and RIO, run on full hourly resolution. A very low number of time slices may imply higher uncertainties in results [18]. Other energy system models are not detected fulfilling the applied criteria. More details about how the mentioned and other energy system models work, can be found at Prina et al. [19].

Detailed models for more realistic scenarios, in order to improve the design of a sustainable energy pathway [35], are still in early development. Hansen et al. [9] highlighted the need for more research on 100 % RE systems across all sectors, especially on energy transition pathways for a better understanding of how to reach it, and the need to link the local and the global level studies. In this sense, a coherent way to find insights is to perform the analysis country by country. However, there would be many challenges to overcome, especially in developing countries [36].

Table 1
Countries and regions with detailed 100 % renewable energy system analyses for a PV share higher than 50 %. Studies are only considered for pathway descriptions from the present to 100 % renewable energy systems no later than the year 2050. Values provided are all for the target year 2050 and for the entire energy system comprising at least the sectors power, heat and transport. All models used are operated as optimisation models.

Country/ Region	PV share	Model	Temporal resolution	Reference
120 in 145 global regions	>50 %	LUT-ESTM	hourly	Bogdanov et al. [20]
Europe	61 %	LUT-ESTM	hourly	SPE [21]
Europe South	58–100 %[1]	PyPSA-Eur	hourly	Victoria et al. [22]
Kazakhstan	81 %	LUT-ESTM	hourly	Bogdanov et al. [23]
Turkmenistan	79 %	LUT-ESTM	hourly	Satymov et al. [24]
Jordan	82 %	LUT-ESTM	hourly	Azzuni et al. [25]
Ethiopia	66 %	LUT-ESTM	hourly	Oyewo et al. [26]
India	70 %	GENeSYS-MOD	time slices (6)	Lawrenz et al. [27]
Nepal, Bhutan	67 %	LUT-ESTM	hourly	Gulagi et al. [28]
Philippines	97 %	LUT-ESTM	hourly	Gulagi et al. [29]
Australia	72 %	OSeMOSYS	time slices (8)	Aboumahboub et al. [30,31]
Mexico	75 %	GENeSYS-MOD	time slices (16)	Sarmiento et al. [32]
Mexico	54 %	Energy PATHWAYS - RIO	hourly	Buira et al. [33]
Bolivia	93 %	LUT-ESTM	hourly	Lopez et al. [34]

[1] Europe modelled in multi-node and interconnected, with several countries above 50 % PV, while entire Europe remains below 50 %; countries above 50 % are Portugal, Spain, Italy, Belgium, Luxemburg, Switzerland, Austria, Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Bosnia-Herzegovina, Serbia, Bulgaria, and Greece.

1.2. Chile as a case study on sustainable energy transition

Chile is an interesting country as a case study for diverse reasons and with great opportunities for potential energy solutions that could have global repercussions. Some of the reasons are as follows:

- Similar to the current global situation, the energy supply is highly dependent on fossil fuels in Chile. The energy-related GHG emissions represent 77 % of the national total in 2018 [37].
- Chile is home to 34 of the 46 most air-polluted South American cities [38]. The most populated cities located in the centre and south of Chile have high concentrations of particulate matter in the air [39]. In most of those cities, the main source of air pollution is the excessive use of firewood for heating [40]. In addition, the country's capital has exceeded ozone standards in the last two decades, which is related to a steady increase in both gasoline and diesel-powered private cars [41].
- Chile is the world's largest copper supplier [42]. The copper extraction, mainly located in the driest area of the planet (the Atacama Desert), has used seawater desalination as an alternative for the water requirement. In addition, this country has the world's largest copper and lithium reserves [43]. Both raw materials will be needed for the global sustainable transition [44,45], putting the country in an excellent position to contribute.
- Chile is one of the first countries to propose updated and more ambitious NDCs and was one of the first to announce its commitment to reach carbon neutrality by 2050. However, the measures are insufficient in terms of its contribution to the Paris Agreement targets [46] and are mainly for the energy sector [47]. Some of the mitigation measures to reach carbon neutrality are based on forest plantations, which could cause more negative than positive impacts to the environment [48,49].
- In the recent years, Chile has been recognised as a world leader among emerging markets for enabling and using sustainable energy [50]. Renewable electricity fed into the grid has exceeded by 3.8 times the mandatory target set by the government [51]. This success in promoting renewable electricity production has occurred without fiscal incentives, subsidies or a feed-in tariff [52]. Yet, GHG emissions in the country are still increasing [37] and it is expected that

the peak of GHG emissions will be reached by 2027 [47]. The ongoing energy transition in Chile, internationally recognised, has been criticised for its structure, which has not been changed to make real progress towards a decentralised and truly sustainable system [53,54].
- Chile is also well known for its enormous RE potential. The country has some of the world's best solar and wind energy resources sites. These sites are located in the Atacama Desert [55] and Chilean side of Patagonia [56], respectively. In addition, Chile is the first South American nation with a geothermal power plant and will be the first to have a concentrating solar thermal power plant. However, Chile has utilised less than 1 % of the total techno-economic RE potential for electricity generation, which is naturally distributed across its continental territory.
- Finally, Chile has been identified as one of the countries that has lowest costs for sustainable RE-based fuels and chemicals production [57–59].

Although the ongoing energy transition in Chile needs to be accelerated, the understanding of the transition is just beginning [60]. Previous scientific work applied to this country have considered at least 60 % of the electricity generated from RE resources [61–63] and did not include heat and transport sectors. Heat sector was recently addressed with a focus on the role of district heating technology for air pollution decontamination and decarbonisation [64]. Three of the four 100 % RE studies [65–67] also addressed the power sector only. Moreover, those studies have not included the whole Chilean territory, and the RE potential from Chilean Patagonia has not been considered in the analysis.

The first 100 % RE study for Chile across all sectors was recently published [60], but it considered the country as one consumption node only. Also, the average annual growth rate of the final energy demand was about three times less than the Chilean government's projection. Furthermore, the pumped hydro energy storage potential of the country was not considered in the study.

In this research, the current policy scenario (CPS) has been simulated, which is based on the energy measures presented at the COP25, in order to compare the findings with three best policy scenarios (BPSs). Each scenario represents a pathway where energy production covers the final energy demand projected by the Chilean government. The final energy demand contemplates the energy required from all activities of the country. All of that was with the aim of analysing the impact of the RE technologies and sector coupling (or a fully integrated energy system) in the energy transition pathways for Chile from a sustainability perspective with a focus on GHG emissions.

2. Methods and data

2.1. Overview of the modelling tool applied

The LUT Energy System Transition model works with a geographical multi-node, high time resolution, dispatch optimisation methodology, single objective investment optimisation methodology, and linear programming technique [19], to obtain cost-optimised scenarios for the whole Chilean energy system. The model has progressively been developed from the power sector [1,68] to the integration of power and heat [69], transport [70] and desalination [71] sectors, respectively. In the case of industrial fuels, the model has the capability to simulate the production of e-fuels (gaseous and liquid) [57,58] based on both green hydrogen [72] and CO_2 from direct air capture units [73], what is also known as power-to-X (PtX), but based on biomass as well. A detailed description of how the model works with all sectors integrated can be found in Bogdanov et al. [20,23].

Fig. 1 illustrates the reference energy system to simulate the energy supply and demand sectors in a fully integrated and interconnected system. For this purpose, the model involves a total of 108 energy-related technologies. A description of the fundamental structure of the LUT model, and the main equations of the target function for minimising the total annual costs for an energy system can be found in the

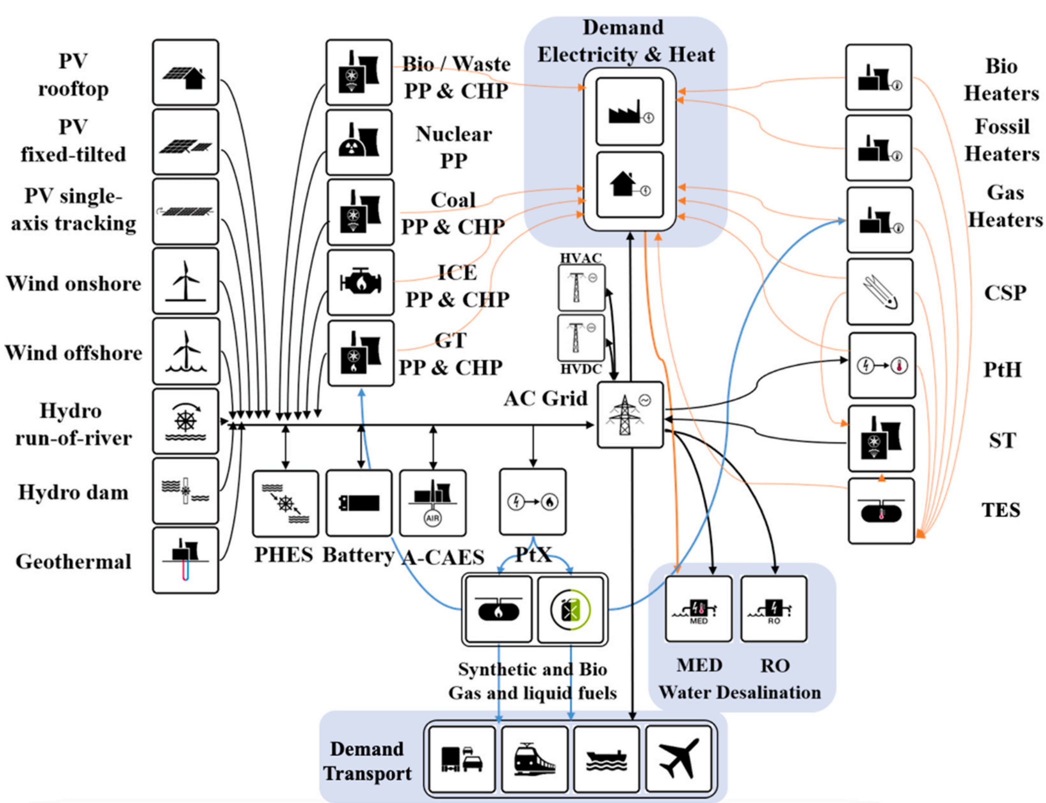

Fig. 1. Schematic representation of the LUT-EST model for all sectors integrated.

Supplementary Materials (see section S2.1).

In this research, the modelling tool was set to simulate four Chilean energy system transition pathways from 2015 to 2050. Each pathway represents a scenario with all sectors fully coupled and Chile fully interconnected by a high-voltage transmission grid. For this interconnection, Chile was subdivided into six zones. A zone represents the subregion in the model equations, and in each zone one main node of consumption was identified. This interzonal connection allows RE resources to be harnessed from anywhere in the country, and ways for supplying energy at the lowest possible cost to be found. An explanation of the country's subdivision is presented in the Supplementary Materials (see section S2.2).

2.2. Country data collection and preparation

Data were collected by region and then prepared by zone as input for the model. The regional data collected were the historical power generation capacities, the final sectoral energy demand in 2015 and the projected final sectoral energy demand until 2050.

The historical power generation capacities were extracted from a dataset of the National Energy Commission (CNE, by its Spanish acronym) of the Chilean Ministry of Energy ('*Minenergia*') which can be found at [74]. These data were allocated by zone and then chronologically ordered from <1960 to 2015 (see the folder *4. Historical power generation capacities*, in the dataset [75]). This is needed to know the end of the lifetime of the existing power plants that should be replaced or renovated during the transition period, in order to consider it as a new investment.

The final energy demand by region in 2015 was acquired from the CNE (which was requested under the Transparency Law), based on its report '*Anuario Estadístico de Energía 2016*' [76]. The regional energy data provided by CNE has a detailed classification of the type of energetics consumed (diesel, fuel oil, natural gas, liquefied petroleum gas, coal, kerosene, electricity, biomass, biogas, motor gasoline, aviation gasoline, aviation kerosene, naphtha, among others) by end-use activity (and sub-activity), such as: transport (road, rail, marine and aviation); industry (paper and cellulose, cement, fishing, steelmaking, sugar, petrochemical and others); mining (copper, iron, saltpetre and others); energy (refining, electricity production, methanol production, gas plants and firewood); residential, commercial and public, and; non-energy use (not include in this study).

The regional final energy consumption by activity was grouped by zone and then re-classified as final energy demand by sector (power, heat, transport and desalination) and by energy form (electricity, heat and fuel). In addition, the final energy demand for each sector was subdivided and categorised as following:

- Power final energy demand was divided into three end-users: residential, commercial (public included) and industrial.
- Heat final energy demand was divided into four end-consumption types: industrial process heat, space heating, domestic hot water heating and biomass for cooking. Heat demand was also categorised as low, medium and high temperatures. This was performed according to Bogdanov et al. [69].
- Transport final energy demand by mode (road, rail, marine and aviation) was divided into both passenger (passenger-kilometre) and freight (ton-kilometre) transportation and categorised into three means: by vehicle type: light duty vehicle (LDV), two wheelers (2W), three wheelers (3W), bus (BUS), medium duty vehicle (MDV) and heavy duty vehicle (HDV); by powertrain technology: internal combustion engine (ICE), battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV) and fuel-cell electric vehicle (FCEV), and; by fuel type: diesel, gasoline, liquid hydrocarbons, biodiesel and bioethanol, hydrogen, liquid natural gas (LNG), jet fuel and electricity. All of that was carried out according to Breyer et al. [77] and Khalili et al. [70].
- Desalination demand includes three end-water-use (in m^3 per day): municipal, industrial (mining included) and agricultural. Seawater desalination demand was projected in zones with a water stress index larger than 40 %, based on Caldera and Breyer [71].

The final energy demand projected for Chile was extracted from a dataset of the long-term energy planning report [78] of the '*Minenergia*'. Here, the available long-term energy planning values were first grouped by zone (see Table 2) and then re-classified by sector and by energy form (see Fig. 2) since data were given by region and by energy end-user activity (transport, industry, mining, residential, commercial and public). The data used as input for this study are provided in the dataset [75] (see the folder *5. Projection of the final energy demand*).

The following step in the data preparation was generating the hourly synthetic electricity load profiles from 2015 to 2050. This was created using the method described in Toktarova et al. [79]. Then, hourly demand profiles for the other energy sectors were generated as well, in order to run simulations for every hour of a year in an optimised manner.

Another step in the country data preparation was estimating the potential of RE resources. To estimate the potential for solar, wind and hydro resources, real weather data were used according to Afanasyeva et al. [80], Bogdanov et al. [68] and Verzano [81], respectively. Sustainable bioenergy potential was estimated based on Mensah et al. [82]. Geothermal potential estimates were done according to Aghahosseini et al. [83]. Additionally, using the Ghorbani et al. [84] method, the pumped hydro energy storage (PHES) potential was estimated [85]. More details of the input data used as energy potential by technology for each zone can be found in the dataset [75] (see the folder *6. Renewable energy potential*).

2.3. Financial and technical assumptions

A complete list of financial and technical assumptions for the technologies involved in the modelling tool, obtained from different sources, is presented in the Supplementary Materials (see section S2.3). These assumptions are based on the most updated learning curves of all the key technologies. These assumptions are a crucial element for attempting to determine a cost-optimal energy transition pathway in a realistic way. This is also key to detect hard-to-abate technologies or sectors, from an economic perspective, since those hard-to-abate technologies or sectors can have a negative environmental impact during the transition period. To calculate the capital recovery factor for each technology, the weighted average cost of capital was set at 7 %.

2.4. Scenarios definition

Four scenarios were set up to analyse different Chilean energy system transition pathways. Three Best Policy Scenarios (BPS) are defined for comparison with the Current Policy Scenario (CPS), all of which are described in Table 3. Comparing the official government policy as the CPS with other scenarios is a standard approach approved by OECD countries where variations can be properly discussed. The assumptions for the CPS were obtained from two government reports: '*Chilean NDC mitigation proposal: Methodological approach and* supporting *ambition*' [47] and '*PLANIFICACIÓN ENERGÉTICA DE LARGO PLAZO – Informe de Actualización de Antecedentes 2019*' [86]. Some of the main assumptions of CPS include decommissioning of all coal-fired power plants by 2040, and reaching 96 % renewable electricity generation by 2050 in order to obtain partial electrification for different purposes, for instance: heating in residential, commercial and public buildings; machines in industrial, mining and commercial activities; road and rail transport modes; and green hydrogen production.

Table 2
Projected final energy demand for each zone from 2015 to 2050.

Zone	Final energy demand, in TWh							
	2015	2020	2025	2030	2035	2040	2045	2050
Chile-North	58.6	62.8	68.3	69.2	71.4	75.7	80.3	88.0
Chile-Central North	54.6	58.6	63.9	65.6	68.3	72.4	75.7	82.4
Chile-Central	111.7	120.4	131.2	134.1	139.4	148.9	157.2	172.6
Chile-South	84.5	92.7	103.1	110.7	119.4	130.4	142.4	158.7
Chile-Aysén	3.4	3.7	4.0	4.1	4.2	4.5	4.9	5.4
Chile-Magallanes	10.2	11.3	12.7	13.8	15.0	16.4	17.9	20.0
Total	323.0	349.4	383.2	397.5	417.7	448.2	478.3	527.0

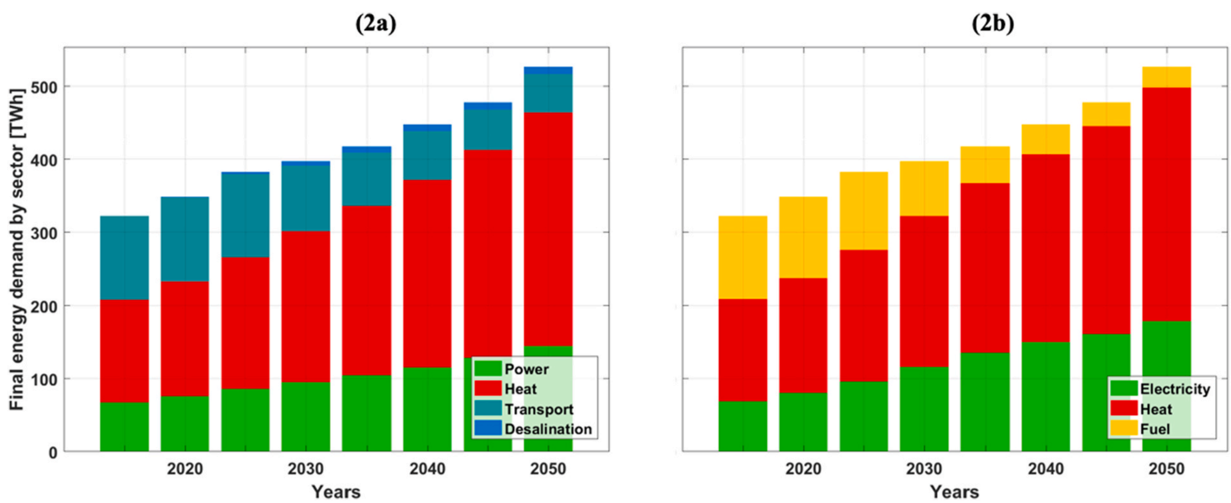

Fig. 2. Final energy demand by sector **(2a)** and by energy form **(2b)** from 2015 to 2050.

Table 3
Scenarios overview.

Scenario name	Description
Current Policy Scenario (CPS)	The CPS contains the latest government targets for the energy sector presented at COP25 in order to achieve GHG neutrality by 2050. This scenario was simulated without GHG emissions costs, however, the assumptions extracted from the government reports have implicit a value of 4.5 €/tCO_2eq during the period.
Best Policy Scenario Unconstraint (BPS-Un)	The BPS-Un does not have any RE target or GHG emissions costs. Here, the research question is what RE level can be achieved on pure economics.
Best Policy Scenario 100 % RE (BPS-100RE)	The BPS-100RE target is to achieve 100 % RE by 2050 and the scenario includes GHG emissions costs. In this scenario, a restriction for electricity exchange through interzonal grid transmission was applied, in order to allow for more utilisation of regional resources.
Best Policy Scenario 100 % RE High Transmission (BPS-100RE-HT)	This scenario has the same RE target by 2050 and the same GHG emissions costs assumptions as BPS-100RE. However, the BPS-100RE-HT does not have any electricity exchange restrictions through interzonal grid transmission.

2.5. Assumptions for sustainability perspective of an energy system and GHG emission analysis

In this work, we assumed a sustainable energy system, defined by Child et al. [87]. This means that an energy system should meet certain criteria in the three spheres of sustainability, such as:

- Economic: use of resources more decentralised and effectively; reduce risk for fuel price volatility, and; promote economic prosperity.
- Social: reduce negative health impacts produced by local air pollution; avert risks from nuclear accidents, waste sites and long-term disposals; reduce resource use conflicts and geopolitical resource conflicts, and; energy mixes with social acceptance.
- Environmental: protection of marine and land ecosystems; protection of rivers and catchment areas by limiting large hydropower plants; reduction of freshwater use, and; do efforts for limiting GHG emission to 1.5 °C compatible pathway.

According to Child et al. [87], those criteria can be achieved by some characteristics related to the supply side and demand side of the energy systems at national and sub-national levels. Some examples include: efficiency gains with high levels of electrification of energy services based on primary renewable energy; flexibility of energy systems through the interaction of high shares of low-cost renewable electricity generation with storage capacities, grids transmission and sector coupling; sustainable fuels production; carbon capture and storage; seawater desalination; and GHG emission reduction. In fact, all these aspects can be addressed with the LUT model, which have been set out for meeting the majority of sustainable criteria of an energy system.

Additionally, for analysing one of the environmental criteria in the four Chilean energy transition pathways in more detail, which is related to achieving global climate target commitment at the national level, the CO_2 equivalent emissions have been assessed. For this, the GHG emission from each scenario was compared with its consistency in the national contribution to hold warming below a 1.5 °C pathway. That means to reduce the absolute GHG emissions to at least 70 MtCO_2eq by 2030, and to at least 38 MtCO_2eq by 2050, according to Climate Action Tracker [88].

To estimate the national absolute emission, the energy-related GHG emissions by scenario were summed at 23 $MtCO_2eq$, which is an average annual from 1990 to 2016 of the emissions from agriculture, industrial processes and product use (IPPU) and waste. This is a conservative assumption since there is no consideration of any emission reduction from those emitter sectors, in other words, we are only considering the GHG emission reduction from the energy sector. In addition, to compare the achievement of GHG neutrality, we assumed −60 $MtCO_2eq$ as the annual absorption capability from LULUCF (land use, land use change and forestry), which is the average annual from 1990 to 2016 as well. Actually, this is also a conservative assumption compared to the −65 $MtCO_2eq$ assumed by 2050, which is based on an afforestation and forest management plan, in the Chilean government analysis to achieve carbon neutrality by that year [47].

Finally, in order to be coherent with some socio-environmental criteria, this study has not considered building nuclear power plants or new large hydropower plants. In fact, large hydropower projects have created historical conflicts in Chile [89,90]. As energy systems based on 100 % RE can reduce the GHG emissions energy-related to zero, and do not use any fossil fuels by 2050, hereafter, we will use the concepts 100 % renewable-based energy system, fully defossilised energy system, and fossil-free energy system, as synonymous with a fully sustainable energy system. This also implies blocking energy crops for energy supply.

3. Results

3.1. Overview of the technology results in the energy supply

In terms of the primary energy demand, both the CPS and BPS-Un would require fossil fuels by 2050, while in the BPS-100RE and BPS-100RE-HT, the primary energy demand would be fully supplied by renewable sources by 2050. In all scenarios, high levels of electrification across all sectors would imply efficiency gains between 24 % and 34 % at the end of the transition period, compared with the current energy systems, based on low electrification rates. More details on major trends in long-term primary energy demand by sector, by energy form, and by efficiency gains are available in the Supplementary Materials (see section S3.1).

3.1.1. Electricity

Fig. 3 shows the electrical installed capacity and electricity generation by technology for each scenario during the transition period. This represents the power technologies that are required through the transition to meet the electricity demand from all sectors in a fully integrated energy system. Results of the new and cumulative installed electrical capacity, electricity generation and curtailment are provided in the Supplementary Materials (see section S4.2).

As can be seen in Fig. 3 (top), the total installed power generation capacity increases from 20 GW in 2015 to 151 GW in the CPS, 215 GW in the BPS-Un, 254 GW in the BPS-100RE and 238 GW in the BPS-100RE-HT, by 2050. The share of RE technologies for the CPS reaches to 95 % of the total installed power capacity by 2050. The corresponding share in the BPS-Un, BPS-100RE and BPS-100RE-HT would be 98 %, 97 % and 96 %, respectively.

In terms of electricity generation, the share of RE would also dramatically increase throughout the transition, as shown in Fig. 3 (bottom). Indeed, for CPS, BPS-Un, BPS-100RE and BPS-100RE-HT, annual average growth rates of 4.4 %, 5.3 %, 5.8 % and 5.7 % respectively are observed. For CPS, out of the 323 TWh generated by 2050, 12 TWh comes from fossil fuel technologies and 311 TWh comes from RE technologies, which represent 96 % of the total electricity generation. For BPS-Un, 98 % of the electricity generated comes from RE technologies by 2050. However, for BPS-100RE and BPS-100RE-HT, the electricity generation is solely supplied by RE technologies at the end of the transition period.

For CPS, the renewable electricity generated by 2050 would comprise the following: 78.7 % solar photovoltaic (PV), 8.4 % hydropower, 5.6 % geothermal power, 2.9 % wind power, and less than 1 % bioenergy and concentrated solar thermal power (CSP) together. In the case of BPS-Un, the renewable electricity generated at the end of the period would come from solar PV (88.5 %), hydropower (6.7 %), wind power (2.4 %), and biopower and geothermal power (less than 1 % combined). In the BPS-100RE, the electricity generated by 2050 would be: 86.6 % solar PV, 5.9 % hydropower, 3.8 % geothermal power, 3.2 % wind power and 0.5 % biopower. Similarly, in the BPS-100RE-HT, the electricity generated at the end of the period would comprise 85.8 % solar PV, 5.9 % hydropower, 4.0 % wind power, 3.9 % geothermal

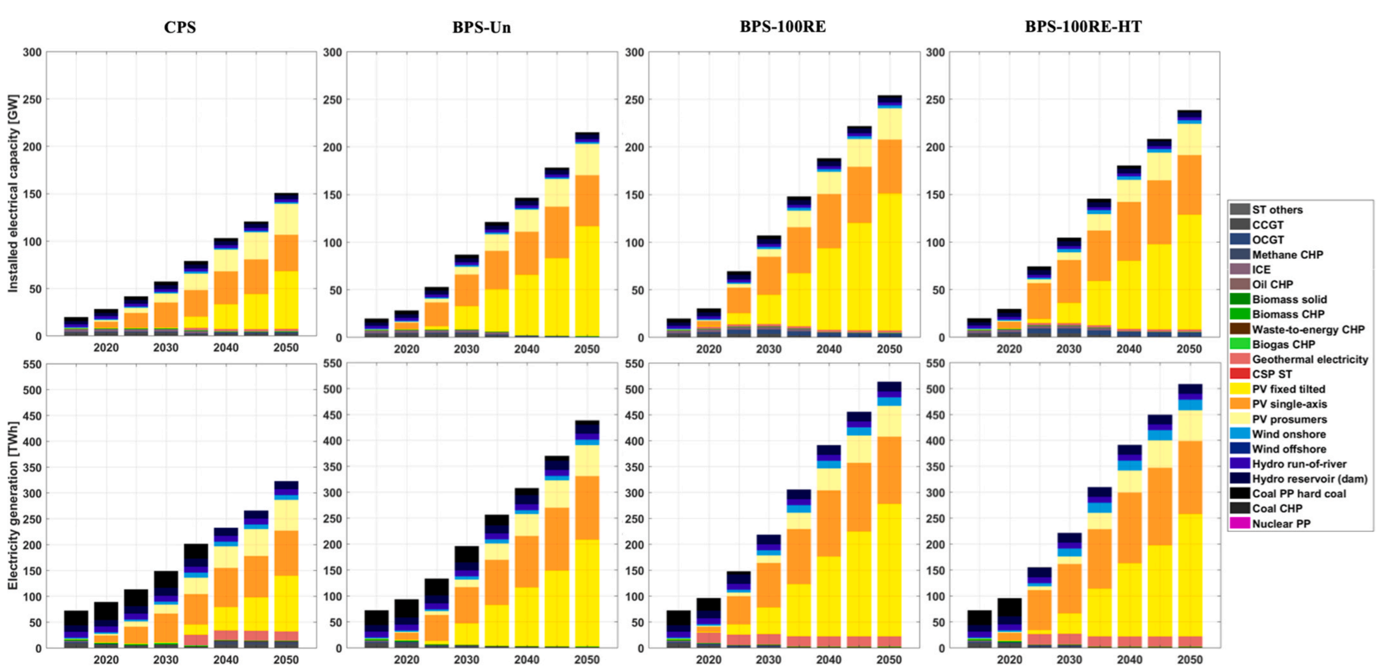

Fig. 3. Cumulative installed capacity by power technology (top) and electricity generation by power technology (bottom) for each scenario during the transition period.

power and 0.4 % biopower.

By 2050, PV prosumers would generate 59 TWh in each scenario (which represents about 40 % of the total electricity demand from the power sector), whereas PV systems, single-axis tracking and fixed-tilted, would generate 195 TWh in the CPS and between 328 and 385 TWh for the three best policy scenarios. These amount to more than 130 TWh in the BPS-Un and 180 TWh in the other two scenarios of the solar electricity supplied at the end of the period. Solar PV technologies will drive the massive electrification across all sectors and the production of sustainable fuels such as synthetic (gas and liquid) fuels produced based on PtX. These results indicate that solar PV technology will be one of the key enablers of the sustainable energy transition in Chile.

To support high levels of electrification in a fully integrated energy system, electricity storage technologies will be needed. An explanation of this is provided in the Supplementary Materials (see section S3.2.1).

According to the results, a high level of electrification becomes one of the vital elements in the transition towards a sustainable energy system. Also, the flexibility provided by a fully integrated energy system, which will be supported by the electricity storage technologies, is crucial to attainment of a fossil-free energy system.

3.1.2. Heat

Fig. 4 shows the total installed capacity for the heat sector and heat generation by technology for each scenario from 2015 to 2050, in 5-years intervals. The results of the new installed heat capacity by scenario, more details of both cumulative installed heat capacity and heat generation by technology for each zone and scenario, heat management results, final energy demand results by type of energy for heat by scenario, and electricity demand results for sustainable heat by scenario, are available in the Supplementary Materials (see section S4.4).

The installed heat capacity, as can be observed in Fig. 4 (top), would increase from 36 GW in 2015 to 86 GW by 2050 for CPS. In the other three scenarios, the installed heat capacity would rise to about 100 GW at the end of the period. In the CPS, 31 % of the installed heat capacity by 2050 would be fossil fuels technologies (25 % gas and 6 % oil), and the remaining 69 % would be comprised of a combination of direct and indirect electric heating (35 %), solar thermal (22 %), biomass (11 %) and geothermal (1 %) technologies. In the other three scenarios, the share of installed heat capacity by technology would be approximately the following: 11 % fossil fuels (mainly gas), 74 % direct and indirect electric heating, 11 % biomass, 3 % solar thermal and 1 % geothermal.

Heat generation would grow at a similar rate during the transition period for all scenarios, as can be seen in Fig. 4 (bottom). By 2050, heat generation would reach to about 370 TWh in the CPS and BPS-Un, and around 350 TWh in the BPS-100RE and BPS-100RE-HT. The results show that bioenergy-based technologies would contribute to heat generation by around 13 % in all scenarios during the transition. In the CPS, fossil fuel technologies would generate 40 % of the required heat by 2050, and the remaining 47 % would be supplied by renewable-based electric heating (direct) and heat pumps (indirect) (35 %), solar thermal (12 %) and geothermal (less than 1 %).

The results for the three best policy scenarios show that renewable energy-based direct and indirect electric heating would dominate the heat generation from the second half of the transition period, reaching about 70 % of the total heat supply by 2050 in each scenario. However, the difference between BPS-Un with the two 100 % RE scenarios is that the heat generation from fossil gas will be fully replaced by renewable-based synthetic fuels at the end of the transition period.

Heat storage technologies will also be needed in a fully integrated energy system for each transition pathway. An explanation of this is provided in the Supplementary Materials (see section S3.2.2).

According to these results, a high level of electrification for power-to-heat (PtH) and the flexibility provided by a fully integrated energy system, which in this case will be supported by heat storage technologies, indicate again that electrification and flexibility are vital elements in the transition towards a fully sustainable energy system.

3.1.3. Fuels

Fuels are used for electricity generation, heat generation and all transportation modes. However, the share used for these purposes varies by scenario during the transition period. The current fuel supply dominated by fossil resources, will be replaced by fossil-free, or sustainable fuels, produced by RE-based PtX, but in different levels for each transition pathway.

Fig. 5 shows the technological requirement for converting fuels by scenario, during the transition period (more details can be found in the Supplementary Materials; see section S4.6). As Fig. 5 shows, water electrolysis to produce hydrogen (H_2), based on electricity, will be the

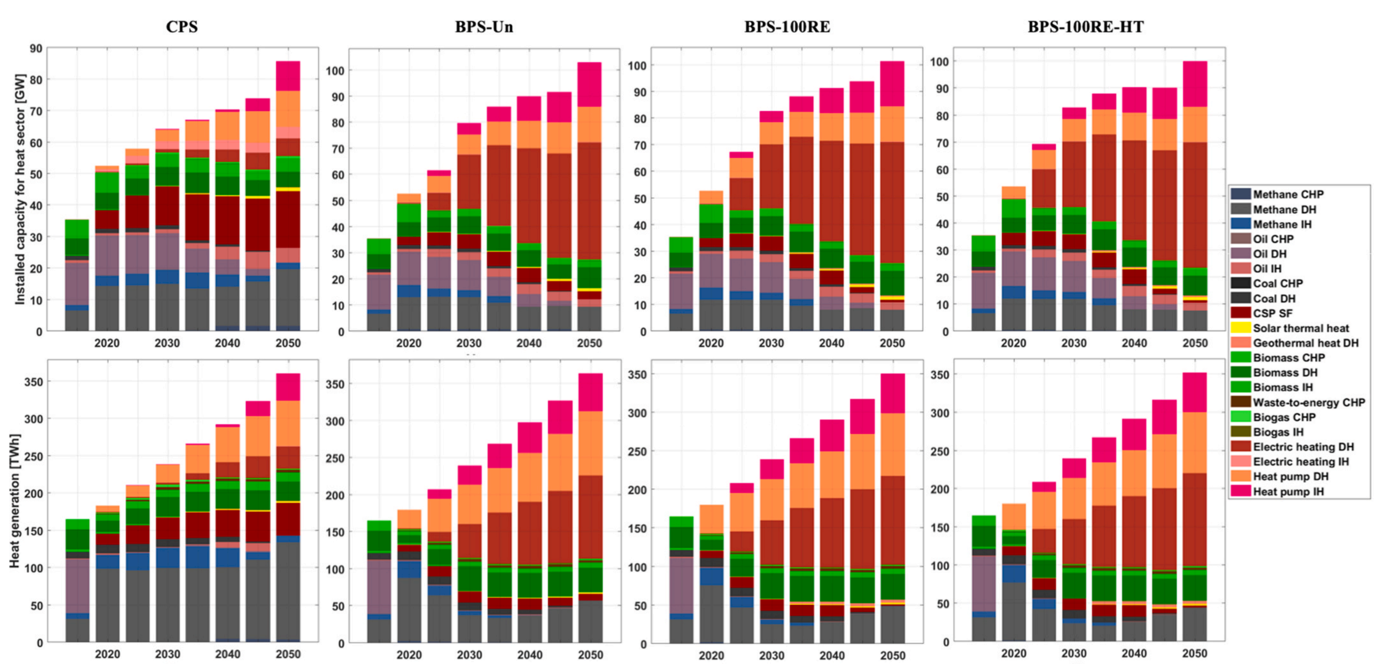

Fig. 4. Cumulative installed capacity by heat technology (top) and heat generation by heat technology (bottom) for each scenario during the transition period.

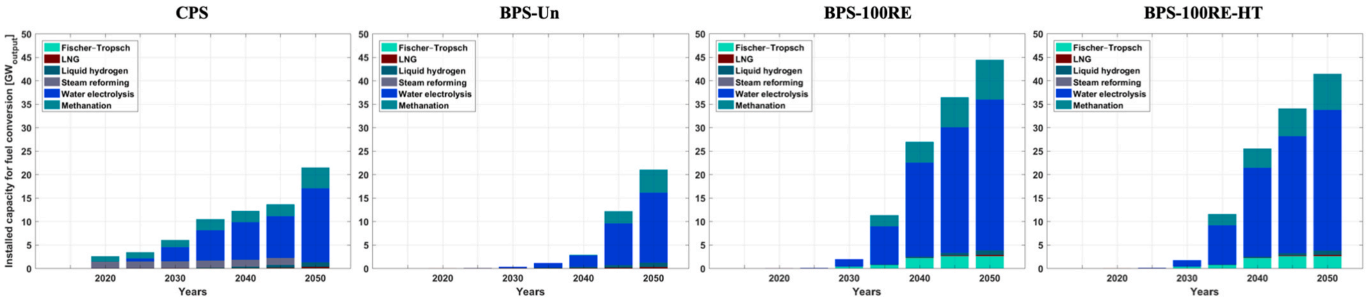

Fig. 5. Cumulative installed capacity for fuel conversion by technology for each scenario during the transition period.

main installed capacity technology for fuel conversion in all scenarios. H_2 can be used directly as final energy fuel in the transport sector, and as a basis for producing different fuels and chemicals.

In the bar graph for CPS (Fig. 5), it is possible to deduce that out of the 22 GW_{output} installed capacity for fuel conversion by 2050, 73 % would be water electrolysis, 21 % methanation, 4 % liquid hydrogen, and, a combination of other technologies would reach less than 2 % (the full load hours differ for each of them, which implies different levels of effective capacity outputs). This is the scenario where the technological installed capacity for fuel conversion will start earlier than the other three scenarios. It is due to the current governmental promotion of hydrogen production for different industrial activities. In the BPS-Un, of the estimated 21 GW_{output} installed capacity for fuel conversion by 2050, 71 % would be water electrolysis, 23 % methanation, 4 % liquid hydrogen, and, a combination of other technologies would reach less than 2 %.

In the BPS-100RE, 19 %, 72 %, 2 %, 6 % and 1 % of the 44 GW_{output} installed capacity for fuel conversion by 2050 would be water electrolysis, methanation, liquid hydrogen, Fischer-Tropsch and a combination of other technologies respectively. The BPS-100RE-HT would have the same installed capacity shares that the BPS-100RE by 2050 but of 41 GW_{output}. The two 100 % RE scenarios show a significant amount of Fischer-Tropsch fuels conversion compared with the other two scenarios. Fischer-Tropsch fuels will mainly be used in marine and aviation transportation modes.

Gas (CH_4 and H_2) storage requirements for each scenario during the transition period are illustrated in Fig. 11 (bottom). The bar graphs for CPS and BPS-Un show that the total installed storage capacity for gas storage would reach 2.6 TWh and 2.8 TWh by 2050, respectively (70 % CH_4 and 30 % H_2 in the CPS, and 62 % CH_4 and 48 % H_2 in the BPS-Un). In the BPS-100RE and BPS-100RE-HT, the total installed storage capacities for gas storage would respectively reach 9 TWh and 7.6 TWh by 2050 (74 % CH_4 and 26 % H_2 in the BPS-100RE, and 78 % CH_4 and 22 % H_2 in the BPS-100RE-HT).

The results indicate that sustainable fuel production will become a third vital element on the path to achieving a fully defossilised energy system. Gas storage requirements for each scenario during the transition period is described in the Supplementary Materials (see section S3.2.3).

3.1.4. Energy supply for the transport sector

Fig. 6 shows, for each scenario from 2015 to 2050, the final energy demand for the transport sector supplied by different types of fuels (top), as well as the electricity demand for sustainable transport (bottom). More details of the results to supply the final energy demand for the transport sector by zone and scenario can be found in the Supplementary Materials (see section S4.7).

As can be seen in Fig. 6 (top), the final energy demand is the same for each scenario during the transition. It will decline from 115 TWh in 2015 to 52 TWh by 2050 and will mostly occur due to the efficiency gains of electrification. This will be made possible mainly through the transition of road vehicles to a combination of electric vehicles with batteries, plug-in hybrids and fuel cells.

One difference between the CPS and BPS-Un scenarios and the two 100 % RE scenarios will be the gradual replacement of liquid fossil fuels with renewable-based fuels. This is mainly to cover the demand for marine and aviation transport modes. By 2050, the 14 TWh of liquid fossil fuels required in the CPS and BPS-Un would become renewable-based liquid fuels in the BPS-100RE and BPS-100RE-HT. The

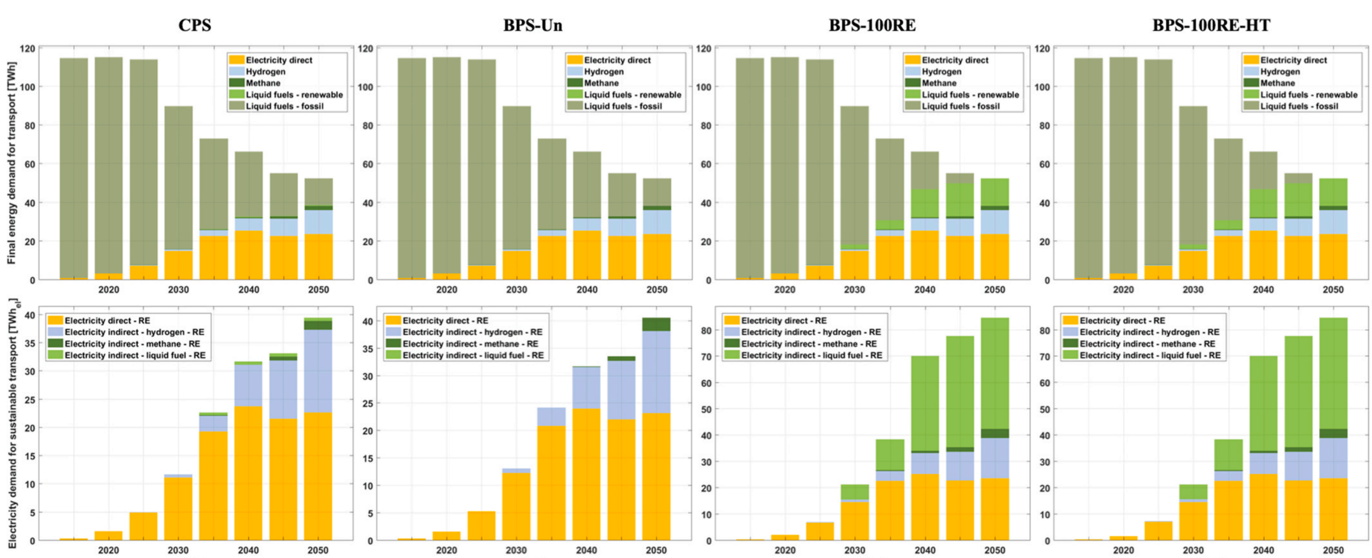

Fig. 6. Final energy demand for transport by fuel form (top) and electricity demand for sustainable transport (bottom) by scenario from 2015 to 2050.

remaining 38 TWh demand for all four scenarios at the end of the period would be covered by electricity (23 TWh), hydrogen (13 TWh) and methane (2 TWh). All of those are based on RE resources.

Another difference between the CPS and BPS-Un with the other two scenarios is the amount of electricity required for sustainable transport, as shown in Fig. 6 (bottom). In the CPS, the total electricity demand would reach to 39 TWh by 2050. This electricity demand would comprise 58 % for direct use, 37 % for hydrogen production, 4 % for methane production and 1 % for liquid fuel production. In the BPS-Un, out of the 41 TWh of electricity required by 2050, 57 % will be for direct use, 37 % to produce hydrogen and 6 % to produce methane. In both BPS-100RE and BPS-100RE-HT, the total electricity demand would reach to 85 TWh at the end of the period. About 28 % of the electricity required will be used directly, 18 % for hydrogen production, 4 % for methane production and 50 % for liquid fuel production.

3.1.5. Seawater desalination production

Fig. 7 shows both the installed capacity required for producing desalinated water and the total projected water demand in Chile during the transition period. Details of the installed desalination capacity and energy demand for desalination production by zone and scenario are provided in the Supplementary Materials (see section S4.8).

As can be seen in Fig. 7, the installed desalination capacity required during the transition period and the total water demand will increase. In each scenario, the dominant technology for water desalination will be seawater reverse osmosis. Although the installed desalination capacity will be the same for each transition pathway, the water storage capacity requirement varies. For instance, BPS-Un will not need water storage, whereas the other scenarios would require different water storage capacities.

The projection of the total water demand in Chile would increase from $2.6{\cdot}10^7$ m^3/day in 2015 to $5{\cdot}10^7$ m^3/day by 2050. The share of desalinated seawater to cover the total water demand would also increase from 1 % in 2015 to 17 % by 2050. It means that desalinated seawater production would rise from $0.1{\cdot}10^9$ m^3 per year in 2015 to $3.1{\cdot}10^9$ m^3 per year by 2050.

The results show that it will require about 10 TWh of electricity for the desalinated seawater production at the end of the period (details of the electricity and heat demand for desalination by zone and scenario can be found in the Supplementary Materials, see section S4.8). In a fully integrated and fully interconnected energy system, as it has been simulated for each scenario in this study, the amount of electricity can be fully supplied by RE. In addition, seawater demand is highest in those zones of Chile where solar PV systems will dominate the electricity supply.

3.1.6. Zonal electricity generation

Fig. 8 depicts the technological transformation of electricity generation by zone, between 2015 and 2050, for each scenario. Additional graphical results on installed power capacity, storage capacities, storage output and more, for all scenarios, are available in the Supplementary Materials (see section S4.9).

As Fig. 8 shows, in 2015, there was a large amount of electricity generated from fossil fuels in all zones of the country. However, by 2050, RE technologies could dominate electricity generation in each zone as well as in each scenario. Solar PV technology would be the pillar for electricity generation, especially in the north, central-north, central and south zones. PV generation would also contribute to the electricity supply in the other two zones located in Patagonia, where wind onshore would also generate a significant amount of electricity. Hydropower plants existing in the current energy mix would be kept during the transition, but its role would primarily be to balance solar PV generation.

Other RE technologies such as bioenergy-based power plants, CSP and geothermal make a minimal contribution to the electricity supply in all scenarios. This is because they cannot compete with the lower generation costs of solar PV and wind onshore technologies, which are based on the world's greatest solar and wind resources, located in the north of Chile and Patagonia, respectively.

The results reveal that the electricity generated in each zone by scenario could be enough to supply the corresponding electricity demand from all sectors by 2050. However, this does not mean that the electricity generated in a zone will all be consumed in the same zone. In other words, depending on the hour of the day and the load demand profile in a zone, the electricity can be exchanged between zones. The differences in electricity generation by technology in each zone by scenario, are directly related to grid transmission capacity and the electricity exchanges through the zonal interconnection (both grid transmissions and electricity exchanges by scenario are described in the Supplementary Materials; see section S3.3). In Fig. 8, this effect can be noticed in the BPS-100RE-HT, where significantly more electricity is generated in the two northern zones of the country, than with the other scenarios, even though the greatest electricity demand is located in the central zone. Hence, this indicates that grid interconnection is a key enabler to the least cost solutions during the transition towards a fully sustainable energy system in Chile, together with solar PV technology.

3.2. Sector coupling

A fully integrated energy system would imply a structural transformation in the Chilean energy system. A graphical comparison of this is illustrated in Figs. 9 and 10. They depict the energy flow of the Chilean energy system in 2015 and by 2050, respectively. The energy flow in Fig. 10 corresponds to the BPS-100RE, and the graphical illustration of three different scenarios can be found in the Supplementary Materials (see section S4.11).

Today, the Chilean energy system, which is close to that of the similar energy flow shown in Fig. 9 and is highly dependent on fossil fuels, is centralised and largely decoupled. As can be seen in Fig. 9, the energy flow in 2015 is inefficient and has no energy recovery options. Approximately 14 % of energy is wasted in the first step, from the transfer of primary energy to useful energy (by 2050, in the BPS-100RE, those losses would be about 0.1 %). In 2015, the power sector was the most diversified in terms of energy sources, where different renewable technologies contributed 24 % (if hydro dams are included, that contribution reaches 42 %). In contrast, transport is the least diversified

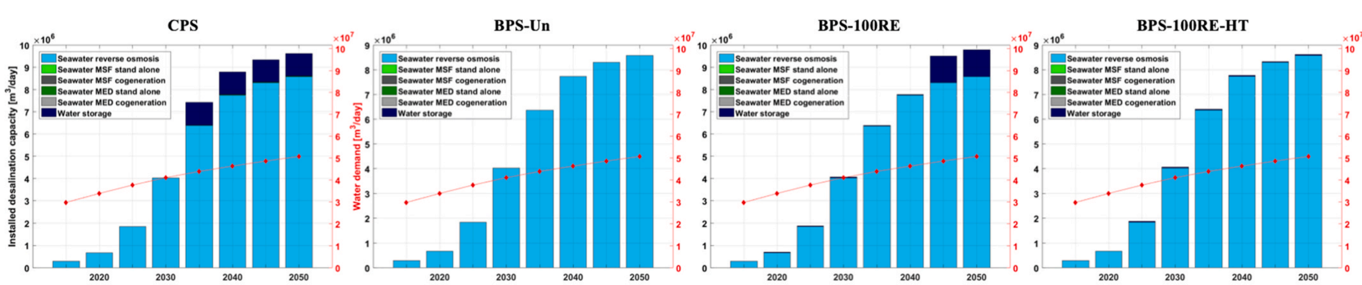

Fig. 7. Cumulative installed desalination capacity by technology and total projected water demand for each scenario during the transition period.

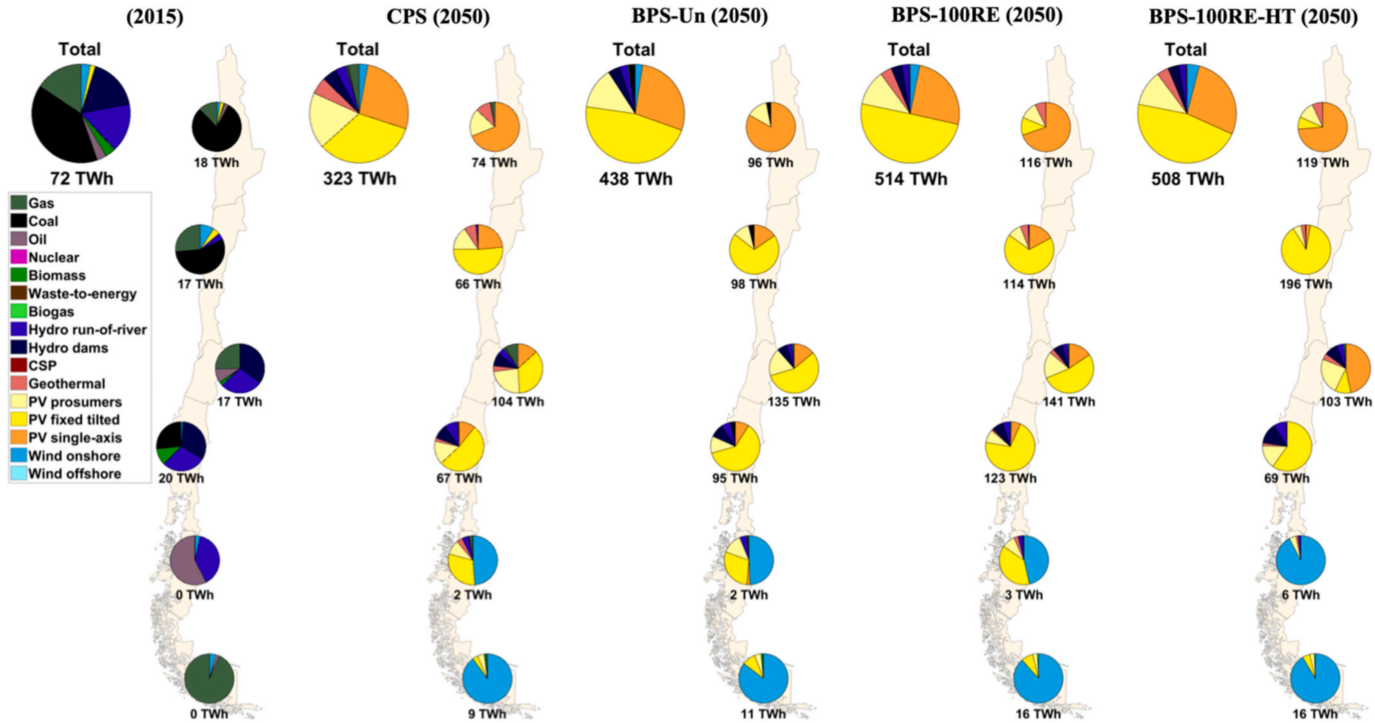

Fig. 8. Comparison of the electricity generation by technology and by zone between 2015 and the four scenarios by 2050. The six zones ordered from the top to the bottom in each country figure are: Chile-North, Chile-Central North, Chile-Central, Chile-South, Chile-Aysén and Chile-Magallanes.

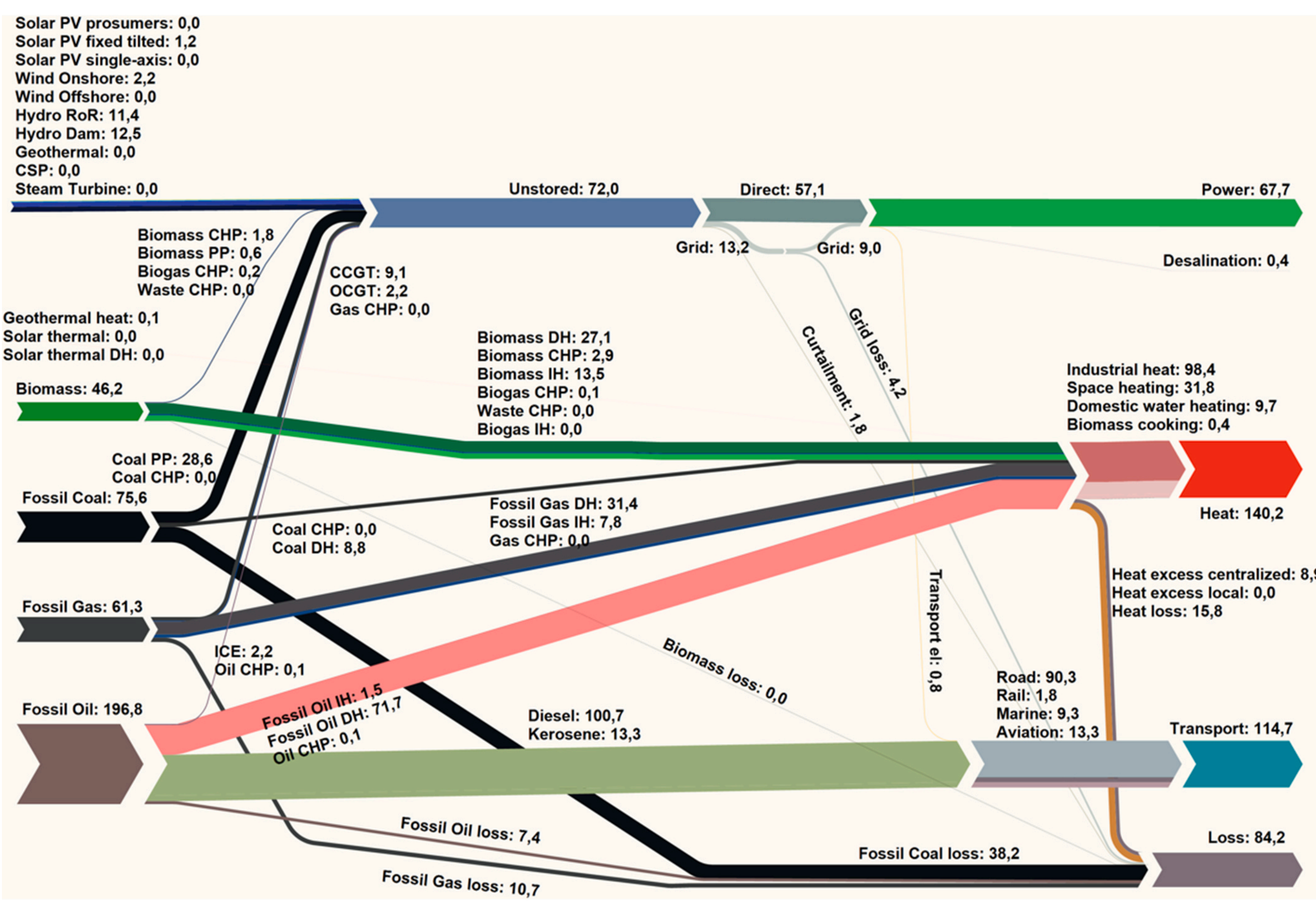

Fig. 9. Energy flow for the Chilean energy system in 2015; values in TWh.

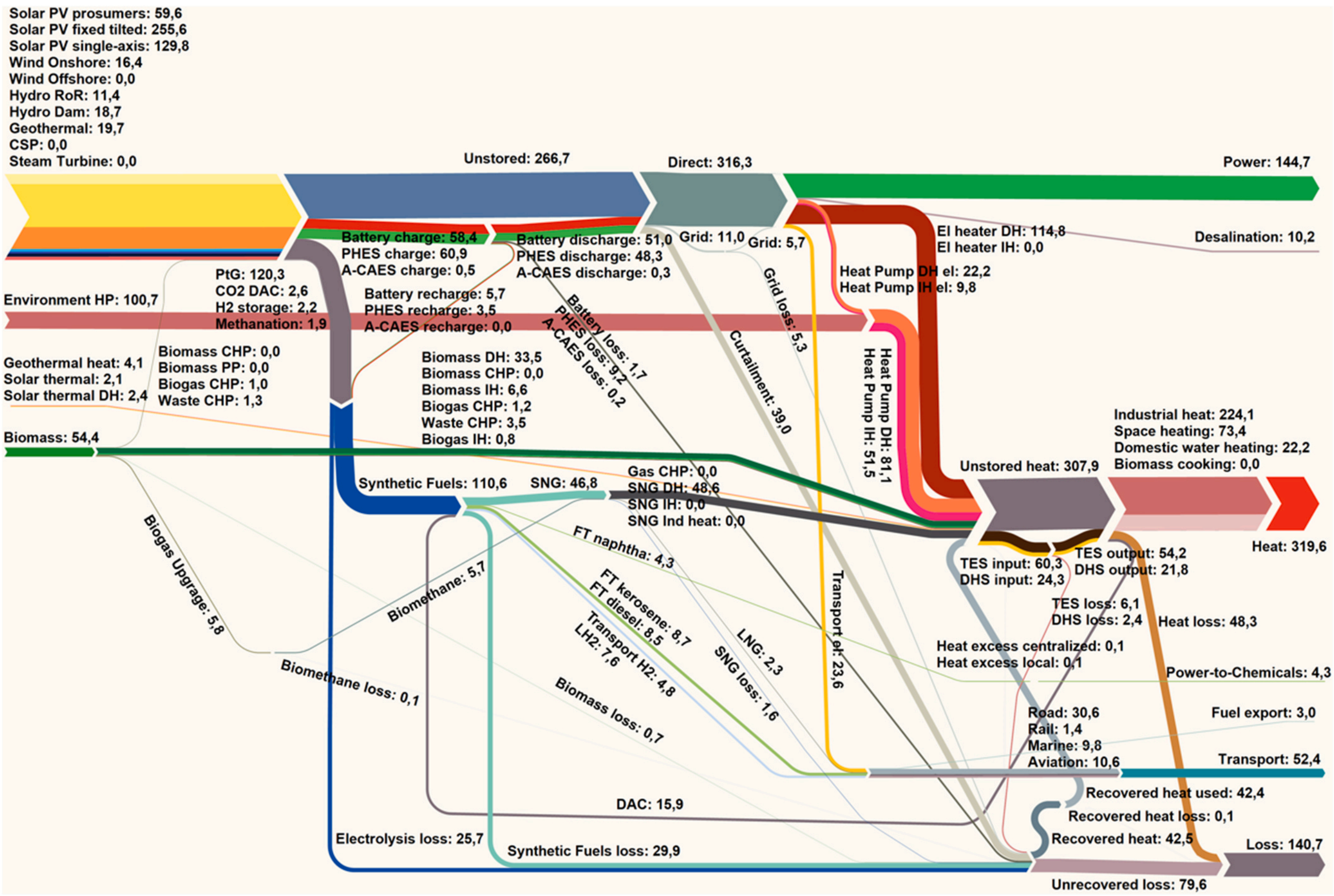

Fig. 10. Energy flow for the Chilean energy system in the BPS-100RE by 2050; values in TWh.

sector as it relies almost completely on fossil fuel (mainly based on oil). Although biomass supply 26 % of energy for the heat sector, this sector is still highly dependent on fossil fuels; oil (44 %), gas (24 %) and coal (6 %).

Fig. 10 depicts the energy flow of a fully integrated Chilean energy system by 2050. There, it is possible to observe the impact of sector coupling in the BPS-100RE, compared to its decoupled stage in 2015. On the one hand, the losses from primary energy to useful energy would be significantly reduced. On the other hand, all sectors would experience a diversification of the energy sources. However, in this case, the fully renewable-based supply would be dominated by solar energy technologies, as pointed out in previous sections.

This fully sector coupled energy system by 2050 includes the integrated use of different energy infrastructures and carriers, in particular, electricity, heat and synthetic (gas and liquid) fuels. Mainly based on renewable electricity, the energy flows through a variety of flexibility options: batteries for short-term storage, PHES and TES for short- and medium-term storage, gas storage for seasonal variations, and a combination of PtH and PtX (power-to-gas and power-to-liquid). Here, green hydrogen is the basis for producing synthetic sustainable fuels (renewable-based hydrogen, methane and Fischer-Tropsch (FT) fuels).

All of this indicates that low-cost renewable electricity and green hydrogen are the core components in a fully sector coupled energy system. This allows a more decentralised, integrated, flexible and demand-oriented energy system to be obtained. The coupling of the sectors gives flexibility in an energy system while at the same time, fossil fuels could be fully replaced with sustainable fuels and GHG emissions could be reduced to zero. As mentioned in previous sections, flexibility is one of the vital elements in the transition towards a fully sustainable energy system. Hence, the results reveal that another key enabler for attaining a low-cost fully defossilised energy system is the integration of the sectors or so-called sector coupling.

3.3. Energy costs and investment

Fig. 11 shows the total annual energy system cost, by sector and main cost category, and Fig. 12 shows the technological investments required, both figures for each scenario during the transition period. All of the energy system cost, investment and fuel cost results by scenario as well as the levelised cost of electricity (LCOE), the levelised cost of heat (LCOH) and the levelised cost of water (LCOW), are provided in the Supplementary Materials (see section S4.12).

As can be observed in Fig. 11 (top), the power sector would keep almost the same share of the total annual energy systems cost during the transition period for each scenario while the heat sector would concentrate the major share during almost the whole period. The share of the total annual energy system cost related to the transport sector would decline in all scenarios, but in CPS and BPS-Un, it would be about half than the other two scenarios at the end of the period. The total annual energy system cost for the desalination sector will have a slight increment in each scenario during the transition period.

The bar graphs of Fig. 11 (top) also show that in the CPS, the total annual energy systems cost by 2050 would be 3.0 b€ higher than in 2015 whereas in BPS-Un, it would be 0.6 b€ lower. In the case of BPS-100RE and BPS-100RE-HT, the total annual energy systems cost by 2050 would be 0.8 b€ and 0.4 b€ higher than in 2015, respectively.

The energy system in BPS-Un would be more cost-efficient than in CPS during the whole transition period. By 2050, the energy systems cost in BPS-Un would be 3.6 b€ lower than in CPS. The total annual system cost in the CPS would be lower than in the two BPS-100RE until

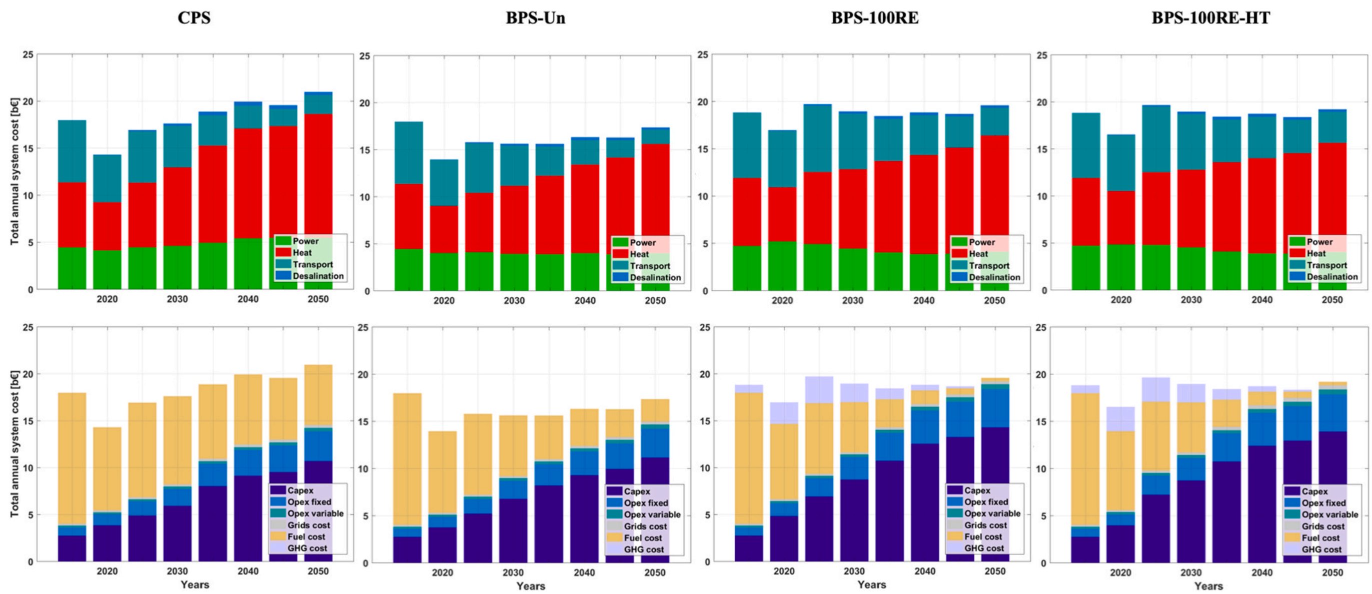

Fig. 11. Annual system costs by sector (top) and main cost category (bottom) for each scenario through the transition.

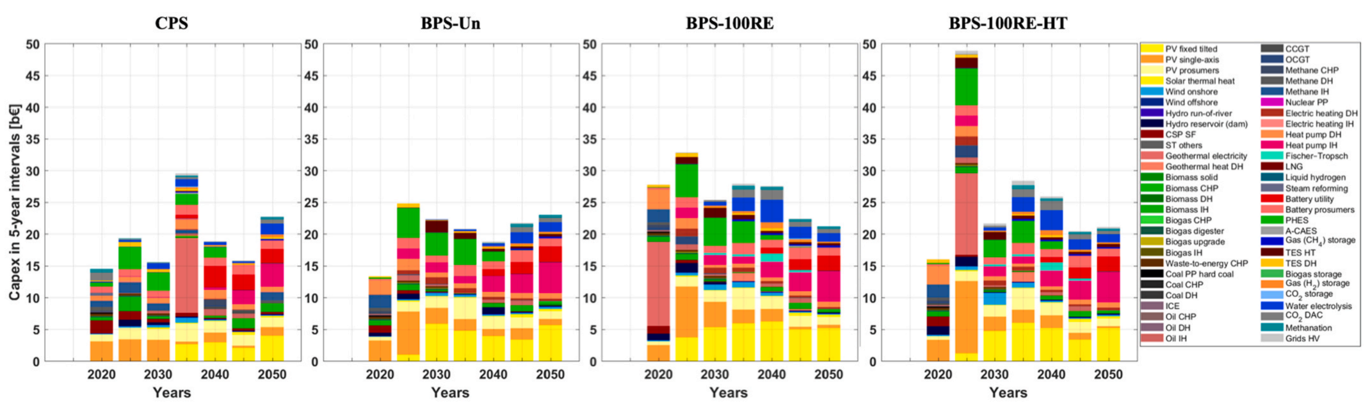

Fig. 12. Capital expenditures in every 5-year interval by scenario during the transition period.

2030. The maximum difference (around 2.1 b€) would be in 2025. This would mainly occur from the CPS's lack of CO_2 emission costs (see Fig. 11, bottom); meanwhile, in the two BPS-100RE, the fossil fuel cost is gradually substituted by capital expenditures (CAPEX), and some operational expenditures (OPEX), based on low-cost renewable technologies. Actually, in both BPS-100RE and BPS-100RE-HT, the energy system would become more cost-efficient than the CPS from 2035 onwards, becoming 1.4 b€ cheaper and 1.8 b€ cheaper at the end of the period, respectively. Although BPS-Un shows that its energy system would be the most cost-efficient option, it is not a fully sustainable solution since it would still be dependent on some fossil fuel.

These results reveal that the cost-efficiency gain in the three best policy scenarios compared with the CPS is an effect of a blend of three key enablers in the energy transition: high level of electricity generated from solar PV systems, the capability of the power transmission grids for facilitating the use of electricity in a different zone than where it was generated, and the flexibility gain through the coupling of the sectors. In other words, the results suggest that the key enablers for a lower cost energy system in Chile are solar PV technology, zonal interconnection and sector coupling. In the case of the two 100 % RE scenarios, they would allow a fully defossilised energy system.

Fig. 11 (bottom) shows that the share of fuel costs will decline at the same time that the share of CAPEX and OPEX will increase for all scenarios during the transition period, but at different levels. The grid cost would be a lower share of the total energy systems cost for each transition pathway. The GHG emissions cost, which had only been considered in the BPS100RE and BPS100RE-HT, will decline to zero at the end of the period. The GHG cost helps to reduce the fossil fuel utilisation in the energy system.

In the CPS, fuel costs would decrease from 13.9 b€ in 2015 to 6.4 b€ by 2050, where 95 % of it would be related to fossil fuels at the end of the period. In the BPS-Un, fuel costs would drop to 2.4 b€ by 2050 (85 % would be related to fossil fuels). While in the BPS-100RE and BPS-100RE-HT, that 0.4 b€ by 2050 will be related to renewable fuels only. CAPEX plus OPEX in the two 100 % RE scenarios will be higher than in the other two scenarios. However, the LCOE (which includes the costs of electricity generation from all technologies, curtailment, storage and transmission) in the three best policy scenarios would be about 9 €/MWh lower than in the CPS at the end of the period. These results indicate that cost reduction is another effect of the three key enablers mentioned before.

Fig. 12 illustrates that the CAPEX will be distributed across a large range of energy-related technologies in each transition pathway. In all scenarios, solar PV technology takes up a significant share of the total investment during the whole transition period. The electric (direct and indirect) heating and energy storage technologies, as well as the technologies to produce fossil-free fuels, would require a large investment from the second half of the transition onwards. From 2020 to 2030, the

BPS-100RE-HT shows the highest capital costs. After that, the investment would be relatively similar to the other two best policy scenarios.

Although the CPS is one of the scenarios with a lower investment, it will have the highest total annual energy systems cost and LCOE at the end of the period. Finally, these results indicate that the two 100 % RE scenarios would require totals of about 26 % and 22 % more investment than the CPS and BPS-Un, respectively, in order to achieve a fully defossilised energy system in Chile by 2050.

3.4. Greenhouse gas emissions

Fig. 13 depicts the GHG emissions reduction by sector and by mode in the transport sector for each scenario, from 2015 to 2050. More details of the GHG emission results by sector and zone for each scenario are presented in the Supplementary Materials (see section S4.13). As Fig. 13 (top) shows, the heat sector would be the large emitter during the whole transition period in the CPS and BPS-Un, while the transport sector would be the large emitter in the two 100 % RE scenarios.

These bar graphs also show that the GHG emissions would decline to 36 $MtCO_2eq$ and 17 $MtCO_2eq$ by 2050 in the CPS and BPS-Un, respectively, and in the BPS-100RE and BPS-100RE-HT it would fall to zero. As can be observed in Fig. 13 (bottom), the large GHG emitter mode in the transport sector is road. In the CPS and BPS-Un, road-related GHG emissions would drop to a similar share to marine and aviation modes.

The reason behind the levels of GHG emissions in the CPS and BPS-Un at the end of the period is due to fossil fuel consumption in the power, heat and transport sectors. In contrast, in the other two 100 % RE scenarios, fossil fuel will be replaced by sustainable fuels, and the majority of which will be produced from green hydrogen and renewable-based CO_2 DAC, such as methane and FT fuels.

The results indicate that the BPS-100RE and BPS-100RE-HT are both fully aligned with the 1.5 °C target. Including GHG emissions from non-energy sectors (agriculture, IPPU and waste) and considering the annual absorption capability from LULUCF, that we assumed, these two 100 % RE scenarios would reduce the national absolute GHG emissions to about 55 $MtCO_2eq$ by 2030, and 23 $MtCO_2eq$ by 2050 (while it should be reduced to at least 70 $MtCO_2eq$ by 2030, and to at least 38 $MtCO_2eq$ by 2050). The BPS-Un could be aligned at the end of the period, if the emissions from the non-energy sectors is reduced by at least 9 % by 2050.

The results also reveal that carbon neutrality could be achieved by 2030 in the two 100 % RE scenarios, and by 2040 in the BPS-Un. Whereas in the CPS, as the government has planned, carbon neutrality will be achieved by 2050; but it will not be compatible with the 1.5 °C pathway [88].

4. Discussion

4.1. Central findings

The results of the four scenarios that were defined and simulated for Chile from 2015 to 2050 indicate that two of the scenarios can be categorised as truly sustainable energy transitions. Although each energy transition pathway has been simulated by setting some of the sustainability criteria (refer to section 2.5), two scenarios show a crucial difference at the end of the period. In the CPS and BPS-Un, 26 % and 12 % of the primary energy demand, respectively, would be covered from fossil fuels. In contrast, the two 100 % RE best policy scenarios (BPS-100RE and BPS-100RE-HT) would reduce fossil fuel utilisation and the energy-related GHG emissions to zero, by 2050. These two 100 % renewable-based energy systems would also be more cost-efficient than CPS, from 2035 onwards. Hence, a fully sustainable energy system, besides covering the demand from all sectors and to meet a series of economic, social and environmental criteria, should be a fossil/nuclear-free fuel energy system, as well.

The energy systems obtained by 2050 as a result of the two 100 % RE best policy scenarios meet almost all criteria that were assumed from a sustainability perspective. In this sense, it is found that a fully sustainable energy system for Chile could be achieved by 2050 mainly based on three vital elements (from a technological point of view) and three key enablers (from a cost-optimal point of view).

The results revealed the following three vital elements for achieving a fully sustainable energy system. The first one was the high levels of renewable-based electrification across all sectors (power, heat, transport and desalination). The second was flexibility, which is provided by a combination of electricity exchanges through the grids and the coupling of the sectors. The third was sustainable fuels production, essentially based on PtX, to produce green hydrogen first and then synthetic gas and liquid fuels. These vital elements are fully in line with several studies [13–16,91–99] applied to different scales in other parts of the world, and with proposed actions by IRENA [100] and REN21 [7] reports.

The three key enablers that have been found for the lowest-cost option, in order to attain a fully sustainable energy system are: solar PV technology, zonal interconnection and full sectoral integration. All of these are in line with those pointed out by Brown et al. [96], especially with respect to the synergies between grid transmission and sector

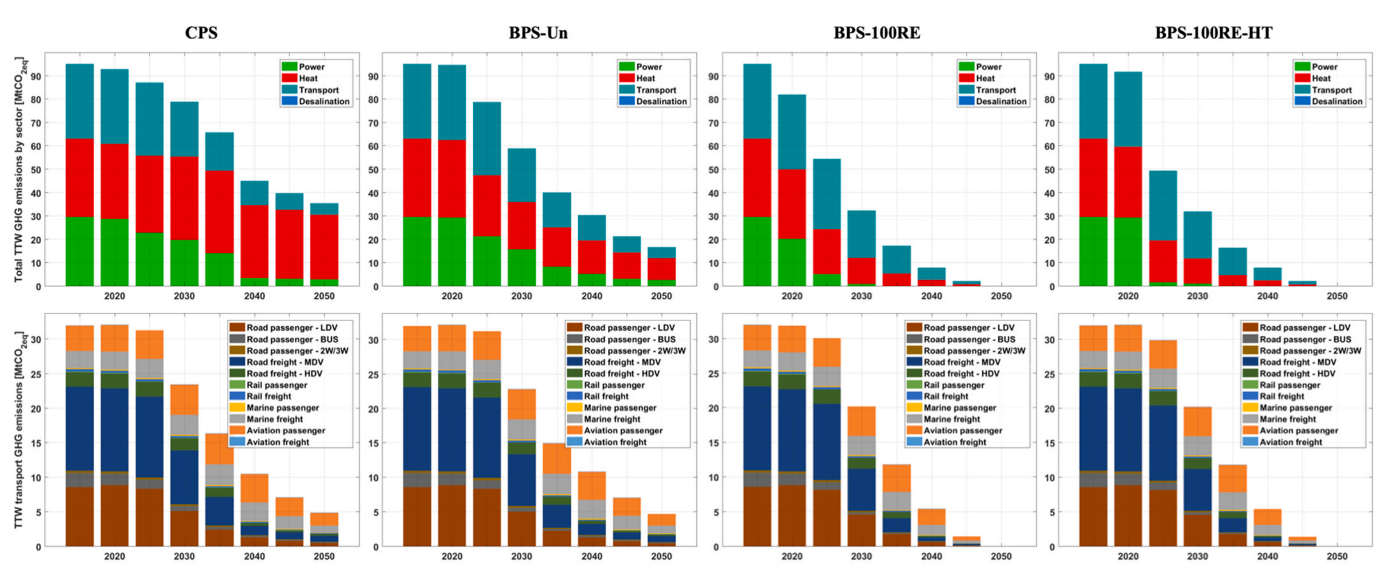

Fig. 13. Greenhouse gas emissions by sector (top) and by mode in the transport sector (bottom), for each scenario during the transition period.

coupling that allow for obtaining the lowest-cost solutions. Low-cost renewable electricity and green hydrogen would be the core in a fully sector coupled energy system. This would allow a more decentralised, integrated, flexible and demand-oriented energy system to be obtained.

Regarding the high levels of renewable-based electrification across all sectors, solar PV would be the dominant technology during Chile's whole energy transition. In the two scenarios, where full defossilisation is achieved, solar PV (fixed tilted, single-axis and prosumers) would contribute about 86 % of the total electricity generated by 2050, which represents about 83 % of the total final energy demand. The remaining share of electricity generation would be composed of about 6 % hydropower, 4 % wind power, 4 % geothermal and less than 1 % biopower and CSP. However, our results that are related to the renewable electricity generation shares differ with previous 100 % RE studies, where Chile has been included in a continental [101] or global [102,103] level, or the country was the study case [60,65–67]. Despite the fact that the total final energy demand considered in our current work was higher than in each of these previous studies, only Haas et al. [65] showed a scenario where solar PV contribution was near 70 %. All other work show a solar PV contribution equal to or lower than 50 %.

Nevertheless, the results of the previous studies are not directly comparable with the findings of this research. On the one hand, some of them [65–67] were only applied to the power sector, and did not consider PV prosumers. Moreover, they did not consider the whole country in their analyses. In the case of Barbosa et al. [101] and Aghahosseini et al. [104], they included PV prosumers in their analysis for the power sector. On the other hand, in the studies in which all sectors were included [60,102,103], Chile was considered to be one node. In this research, the country is divided into six nodes. This could explain the differences in results, especially in the power generation shares since the modelling tool chose the lowest cost option that existed near the energy demand, but also due to the electricity exchange between the zones. This has drastic consequences for the share of wind energy, since it would be a highly attractive source of electricity, if the excellent wind resources would be closer to the demand centres. This effect is well considered in this research, but cannot be correctly addressed in a single-node study.

Additionally, the most updated technological costs and learning curves have been used for the financial assumptions, which led to some variation in the results with the previous studies. However, there is a great difference in the work performed by Gaete-Morales et al. [67]. For example, in that work (published in 2019), they assumed PV costs based on a learning rate from studies carried out in 2010–2014. In other words, the PV costs utilised by Gaete-Morales et al. [67] in 2050 seem to be the PV costs assumed by about 2030. As a consequence, the results show a PV contribution of 20–33 % by 2050 between the scenarios, whereas the current findings indicate a PV contribution of 79–89 % between the four scenarios. In summary, our study is the first applied to Chile, including all sectors integrated and contemplating the whole country fully interconnected by six nodes, and was performed with the most updated cost assumptions for energy-related technologies.

4.1.1. Opportunities and challenges

The results of this research suggest that a technological transformation, from the supply side, towards to achieve a fully defossilised electric system in Chile is feasible. It would mainly be based on the world's greatest solar resource located in the Atacama Desert [55] but also based on the good solar conditions in almost all Chilean territory [105]. PV prosumers could reach 33 GW of installed capacity by 2050 throughout the country, and, in the transition pathway with more installed capacity of solar PV systems (fixed tilted and single-axis), this technology would reach 201 GW at the end of the period. This installed capacity is one sixth of the available techno-economic PV potential in Chile, reported by the Chilean government [106] (RE potential of Patagonia is not included in that report). It means that those around 1200 GW of solar PV potential was estimated without including: areas with capacity factors less than 0.24, areas with ground slopes over 10°, urban areas and human settlements, rail lines and roads, natural parks, protected areas, and water bodies. Moreover, Patagonia's solar PV potential is not included in the government report. In fact, Patagonia has some areas with solar irradiation levels above 4 kWh/(m^2·d) [107]. Also, some of the most populated cities and towns in Patagonia have a solar PV potential comparable with the centre of France and even better than Freiburg, one of the sunniest places in Germany [108]. All this demonstrates the great opportunity of Chile for PV deployment in all its regions and for materialising a sustainable energy transition in a more decentralised manner.

In addition to the solar power potential in Chile, the existing electrical infrastructure is another advantage for attaining a fully sustainable energy system. The national electric system already interconnects 14 of the 16 geo-administrative regions of Chile. This is analogous to the interconnections that were used for the Chile-North (CL-N), Chile-Central North (CL-CN), Chile-Central (CL-C) and Chile-South (CL-S) zones in this study. According to the findings, in terms of the electricity exchanges throughout the transmission grids, the majority of the energy would flow from CL-CN to CL-C. The CL-CN zone is located in the Atacama Desert, and the CL-C zone is in the place with the highest energy demand.

Despite Chile having sites with the world's highest wind energy potential in Patagonia [56], the finding indicates that the interconnection of the two regions located there with the rest of the country is not needed. In other words, the excellent wind potential in Patagonia has no chance against the excellent solar potential located in the north of the country. This is mainly due to the distance from the sites with the highest energy potential (the Atacama Desert and Patagonia) to the large consumption node. Therefore, it can be suggested to increment by at least 1.5 times the capability of the existing transmission grids from the Atacama Desert to CL-C zone (where the highest energy consumption node is located and more than 50 % of the Chilean population lives). This will help facilitate the sustainable energy transition by harnessing the sun's energy through PV technology.

Furthermore, copper extraction, which is one of the most energy-intensive industries in Chile (its projected final energy demands have been included in this study), is mainly located in CL-N and CL-CN zones, where solar resources are higher [109]. Here, there is also a synergy between solar energy and seawater desalination [110]. All this would allow Chilean copper mining to become a cleaner process [43,111]. According to Hass et al. [112], the Chilean copper mining electrical supply could become 100 % solar based by 2030. But also, according to Moreno-Leiva et al. [113], copper mining needs a multi-vector system design to supply its energy (electricity, heat and fuels) and water demand, with an appropriate operational flexibility. Therefore, the current approach and results are in line with achieving clean copper production sooner in Chile. In addition, due to Chile being the world's largest copper producer with the largest reserves of copper [43], the country can drive the clean production of this raw material that is needed for the global sustainable energy transition.

The large marine coast extension in Chile suggests an opportunity to face some climate change impacts at the local level, related to water issues and beyond. Through renewable energy based seawater desalination, it would be possible to reduce issues associated with water scarcity and groundwater abstraction. The desalination plants would also help the water cycle, supporting both the adaptation to, and mitigation of climate change impacts. This results in providing abundant water for human use, while helping to preserve and restore ecosystems [114]. According to the results, the energy needed for the seawater desalination process could be fully supplied by renewable resources. It can help to supply the water-intensive demand for copper and lithium extraction in Chile. The Atacama Desert also contains one of the world's largest lithium reserves [115] (about 25 %). Thus, the renewable seawater desalination plants could also contribute to the clean extraction of copper [116] and lithium [115]. Both raw materials are needed for global sustainable energy transition as well [44,45], where lithium is most critical [117,118].

All this means that Chile could reach a fully sustainable energy system by 2050, using only about 10 % of its techno-economic RE potential for electricity generation distributed throughout the continental territory. However, the economic competitiveness of some technologies in the coming years, particularly solar PV and wind onshore, could increase the available techno-economic RE potential of this country.

In this sense, another opportunity for Chile to not only carry out a fully sustainable energy transition, but also contribute to the global energy transition, and utilise the full potential to produce sustainable RE-based fuels. The Atacama Desert and Patagonia have been identified as two of the best sites in the world for producing green hydrogen, synthetic gas and liquid fuels, and even chemicals [57–59]. It could even become a hot spot for CO_2 direct removal as part of a global net-negative post-2050 economy [119]. In addition to green hydrogen that can be used directly for energy purposes, it is the basis for producing synthetic methane, synthetic liquified natural gas, and synthetic diesel, gasoline and jet fuel, based on the Fischer-Tropsch process. These PtX-based sustainable fuels are essential as replacements of fossil fuels used in marine and aviation transportation, with no technological change needed in the transport modes. This would take place in the second half of the transition period, allowing an attainment of a fully defossilised energy system in Chile by 2050. Hence, Chile has the potential to contribute to the global sustainable RE-based fuel supply and even to the production of global sustainable RE-based chemicals. Chile also has the opportunity to become a green hydrogen producer where this chemical element can be used as an industrial raw material for manufacturing glass, metals, fertilisers, among other.

However, the fully sustainable energy transition will not be without challenges. From a socio-environmental point of view, clean copper and lithium production is one of the biggest challenges in Chile [115], but it is also a global concern [120]. In the same sense, the socio-environmental conflicts on the integration of large-scale RE power plants into the energy mix could face challenges as well [54,121].

However, in Chile, there is more willingness to pay for RE technologies other than hydro dams [122]. Nevertheless, another challenge related to social acceptance could emerge according to Flores-Fernandez [54]: '*The incorporation of non-conventional renewable sources to the energy matrix has not modified the technocratic model of market-based management, the ownership structure of the projects, nor has it implied an advance towards democratic and decentralised energy systems that promote local development and the effective participation of communities in energy decision-making.*'

Reaching the levels of power prosumers shown in the results seems to be another challenge. In the case of the PV prosumers segment, the challenge is directly related to the current regulatory framework. In Chile, although it is legal to install grid-connected PV systems, it is under a net-billing scheme. If this scheme is kept during the transition period, the contribution of the PV prosumers, especially from the residential segment, could be significantly limited [108]. That would cause repercussions to the contribution of this segment to the decarbonisation and decentralisation of a fully integrated energy system [123], but also to its contribution to reducing air pollution in Chilean cities with high levels of particulate matter [124,125].

From a techno-economic point of view, a scenario has been defined that does not have a 100 % RE target by 2050 or GHG emissions cost (the BPS-Un). This is to identify the segments and sectors that are hard-to-abate. Based on this, it has been found that fossil fuel requirements, especially for marine and aviation transport modes and the high temperature segment of the heat sector, are the most hard-to-shift. In fact, Fischer-Tropsch fuel production is not considered in the current energy targets of Chile's government. According to the results in the BPS-Un (but also in the CPS), some fossil fuels would still be used in the power sector but more in the heat sector by 2050 as well. This statement coincides with the part of the current government energy target that has less ambition for achieving carbon neutrality so far.

In the heat sector, technological transformation seems to be a big challenge in Chile. This challenge is essentially related to the investment cost and energy price. On the one hand, heat pumps and district heating systems have high capital expenditures in this country. In the case of a heat pump, it would be more of a challenge for the residential segment, which is the second largest heat demanding segment in the country but with less purchasing power. In fact, the residential segment is one of the main responsible for particulate matter emissions in Chile due to the use of cheap and bad quality woodfire for heating [126]. However, in the case of district heating systems, they show an interesting potential that have two-fold function in Chile (decarbonisation and air pollution decontamination), where a national district heating plan could be aligned with a 100 % RE target [64]. On the other hand, the current electricity price in Chile is not competitive yet with other forms of energy (such as firewood and fossil alternatives) for heating purposes in most parts of the country. Firewood is the cheapest fuel option for heating purposes in most parts of the country [40,127].

However, more than technical or economic challenges, it seems that political, institutional and cultural barriers are the main obstacles for a 100 % renewable-based energy system [128,129]. Actually, and in accordance with the latest REN21 report [7], the support from effective policies has been key to the advancement of RE technologies in the power sector, while heat and transport sectors have had less policy attention, despite the fact that they are large energy consumer sectors.

4.1.2. Energy cost and investment

Comparison of the four pathways simulated shows that the BPS-Un would provide the most cost-efficient energy system during the whole transition period. The two 100 % RE scenarios would give more cost-efficient energy systems than CPS, from 2035 onwards. By 2050, the total annual energy system cost under the CPS scenario would be 3.6 b€, 1.4 b€ and 1.8 b€ higher than BPS-Un, BPS-100RE and BPS-100RE-HT, respectively. Although in the BPS-Un the total annual energy system cost would be the cheapest option, it would have a crucial distinction from the other two best policy scenarios. The two 100 % RE scenarios would imply a fully defossilised energy system by 2050.

Nevertheless, in terms of LCOE, the three best policy scenarios would not be significantly different. After that, BPS-Un would have on average a 14 % lower LCOE than the two 100 % RE scenarios from 2020 to 2030, and three best policy scenarios would have almost the same LCOE from 2035 to 2050. Moreover, these three best policy scenarios would have lower LCOE than CPS from 2030 onwards, reaching a LCOE of about 25 % lower than CPS at the end of the transition period.

The difference of 0.4 b€ in the total annual energy system cost by 2050, between BPS-100RE and BPS-100RE-HT, is mainly an effect of the energy transmission through the grid. Because in the BPS-100RE-HT there is no limit to the electricity exchange between the interconnected zones, it would imply 16 GW less of installed power capacity, 1 GW less installed energy storage capacity, and 3 GW less electrolyser for green hydrogen production, compared with the other 100 % RE scenario. Consequently, this would also imply less investment cost in the BPS-100RE-HT, but it is not significant compared with the difference between both 100 % RE scenarios with investment in the CPS.

In the CPS, the total investment would be about 26 % lower than in each of the two 100 % RE scenarios. However, the two best policy scenarios would allow a fully defossilised energy system to be achieved by 2050. Furthermore, this does not include the costs saved from reducing the health impact. In this sense, according to one of the key insights recently reported by IRENA [100]: '*Low-carbon investment would significantly pay off, with savings eight times more than costs when accounting for reduced health and environmental externalities.*'

In any case, it can be suggested to implement both a feed-in-tariff scheme (at least for PV prosumers) and promoting a weighted average cost of capital (WACC) lower than 7 %. Lower WACC values can make a RE project much more competitive, especially a PV project, as was pointed out by Vartiainen et al. [130]. Meanwhile, because Chile has a tax of only 4.5 €/tCO_2eq, it can be effective to apply an increment to the current CO_2 emissions taxes, following the call from 27 Nobel Prize-winning economists [131]. These three suggestions are intended to accelerate the sustainable energy transition in Chile and also to increase the contribution that the country can make to the global sustainable energy transition through the production of RE-based fuels and clean raw materials.

4.1.3. Greenhouse gas emissions

Clean technologies supported by a cost-efficient solution would cause a strong reduction of the negative environmental impacts. With a 100 % renewable-based energy system, it is possible to go beyond GHG reduction, and produced particulate-free clean air at a local level. In Chile's case, this would solve the air quality problems related to high levels of particulate matter during winter periods, reducing negative impacts on citizens' health.

Focusing particularly on GHG emissions analysis, the obtained results reveal that the CPS is not in line with the pathway for limiting warming to 1.5 °C. This aligns with the analysis from Climate Action Tracker [88] so far. In the case of the BPS-Un scenario, it could be consistent with the 1.5 °C pathway at the end of the period, but it would be directly dependent on the GHG emissions reduction from other non-energy emitter sectors. In contrast, the two 100 % RE scenarios not only are fully aligned with the pathway for limiting warming to 1.5 °C, they would also allow Chile to reach carbon neutrality by 2030. These 100 % RE policy scenarios also imply that Chile could become a negative emitter country from 2035 onwards.

However, from the point of view related to the three spheres of sustainability, to achieve a fully defossilised energy system is more important. This would be possible thanks to a transition towards a fully cross-sectoral integrated energy system. In Chile, this requires using about 10 % of its available techno-economic RE potential for attaining a fully defossilised energy system. Furthermore, that energy system would be more cost-efficient than the CPS by 2050.

Chile only emits 0.24 % of the global GHG emission. However, all countries that emit less than 1 % of the global GHG emissions, total to about 24 % of the total emissions [132]. On the other hand, Chile probably has better RE resources than those other countries, but those countries could have less final energy consumption per capita than Chile. Nevertheless, due to most of those countries being located in the Sun Belt (between latitude ±45°), they could achieve a 100 % renewable-based energy system by 2050, as well as those 17 countries that are major emitters [20,133]. In any case, Chile has the potential to contribute through sustainable, RE-based fuel production. Chile can also contribute with the clean production of raw materials (copper and lithium) to the global energy transition. Additionally, Chile could even contribute with RE-based chemical production. All of this could be done in order to accelerate the attainment of a global post-fossil fuels economy.

4.2. Limitations of this study

This study has simulated four energy transition pathways where energy needs from all sectors in Chile are covered. In this regard, the LUT model tool delivers the newly installed electric capacity required for each of the six zones that have been contemplated. However, the specific location of those utility-scale power plants is not provided in the results. The solar PV capacity, of more than 180 GW, in the two 100 % RE scenarios are not constrained by land area. Nevertheless, in order to reduce social conflict and environmental externalities, the specific location of the new power plants should be assessed in more detail. It can be made following the strategies purposed by Matamala et al. [121].

From a geographical and sectoral perspective, only fully interconnected and integrated option of the energy system for each scenario has been addressed. Medium and low voltage transmission lines have not been considered in the analysis. Nevertheless, in the case of Chile, considering that the world's largest solar and wind energy potential are both located in the extreme tips of this country; some geographical or even sectoral separation could give more value to some zones. Perhaps, it could also reduce the total energy systems cost or investment. However, this needs to be investigated further.

Another limitation of this study is the fact that the so-called smart charging of battery-electric vehicles and vehicle-to-grid flexibility have not been included, but the potential impact in an energy system is discussed by Child et al. [134]. In the same sense, an analysis in a higher local level applying the intelligent cyber-physical system approach [135] or to city-scale [97] could show some differences as well. However, its impact at the national level would be also needed to be evaluated.

In any case, a more decentralised energy system based on RE resources would imply some positive socio-economic and socio-environmental impacts. RE technologies are showing a constant increase in the number of employments rates [136]. Also, the job creation during the transition towards a 100 % renewable-based energy system that seems to be highly attractive [137,138]. In addition, that kind of transformation of the energy system by 2050 is also indicated in a higher gross domestic product growth [100]. The social health cost and other environmental externalities would give more insight into the positive impacts of a fully sustainable energy transition. As all these socio-economic and socio-environmental aspects were not addressed in this study, it is suggested to perform an in-depth analysis of them. This is in order to understand in a more holistic manner the impacts of the transition towards a fully renewable-based energy system. But more importantly, to justify why we need an acceleration of defossilising the energy system to attain the climate targets by 2050.

4.3. New research opportunities

In addition to those socio-economic and socio-environmental aspects that are outside of the focus of this research, some geographical characteristics that distinguish Chile from the other countries, together with some natural resources and its enormous RE potential distributed throughout its continental territory, make this Andean nation an interesting study case. In other words, Chile has a unique situation to research concerning ways to produce solar fuels, such as those reported by Lips et al. [139], Ardo et al. [140] and Detz et al. [141], and to become a global fossil-free fuel and chemical production pole as well.

Based on the world's best solar and wind energy resources, studies have identified Chile as one of the world's best countries to produce low-cost RE-based fuels and chemicals [57–59]. However, the Chilean export potential of green hydrogen as an industrial raw material and PtX-based fuels and chemicals has not been studied. In addition to the techno-economic refining for the green hydrogen and ammonia production suggested by Armijo and Philibert [59] and Fasihi et al. [142], the impact on the energy system structure (i.e. how much of both power and storage installed capacity is needed for that, where it will be better to install, and how the energy demand profile would vary) in this country needs to be analysed. On the other hand, Chile's contribution to accelerate the global sustainable energy transition and the attainment of a post-fossil fuels economy could also be investigated.

On the other hand, although it has not been considered in this work a scenario with fossil carbon capture and storage (CCS) technologies (in order to avoid additional water stress and air pollution), it could be interesting to compare the total costs of a BPS with zero emissions with a scenario considering a full set of fossil CCS technologies and also negative CO_2 emission technologies [119,143,144]. This is an open question, especially if it is considered what Xiao et al. [145] and Victoria et al. [146] found about incorrect PV cost and incorrect PtX modelling leading to stark distortions in the results of energy scenarios. Therefore, a highly sophisticated method is required and this case requires more investigation.

5. Conclusions and recommendations

In this study, Chile's energy transition was modelled based on the current policy scenario and compared with the three best policy scenarios. Each transition pathway was simulated by subdividing the whole country into six zones, including its energy demand from all activities into four sectors (power, heat, transport and desalination), and contemplating a fully interconnected and integrated energy system, carried out in full hourly resolution. This is the first study applied to Chile under these characteristics.

The results confirm that attaining a fully sustainable energy system in Chile by 2050 is technically-feasible, and they also reveal that this scenario could be more cost-efficient from 2035 onwards than the current policy scenario to achieve carbon neutrality. Under the two 100 % RE transition pathways, Chile could reach carbon neutrality by 2030, and could become a negative emitter country by 2035. In addition, the two 100 % RE scenarios would be pathways consistent with limiting warming to 1.5 °C, and would also imply that a fully defossilised energy system could be achieved by 2050.

Furthermore, a 100 % RE scenario would use about 10 % of the available techno-economic RE potential for electricity generation in Chile. The two 100 % RE scenarios would imply a more decentralised energy system that meets the majority of assumed sustainable criteria, and water scarcity would be covered by RE-based seawater desalination. However, socio-economic and socio-environmental benefits need to be evaluated in order to obtain more justification for accelerating the sustainable energy transition. Also, it is necessary to investigate how society can accept and use the technological changes discussed in the scenario and what is the most important barrier to government policy regarding the energy transition in Chile.

All of that would be possible in Chile mainly because the country has the world's best solar resource. This enables supplying low-cost electricity to support PtX-based sector coupling, not to mention the rest of the RE potential distributed throughout Chile's territory. Actually, in a 100 % RE system, solar PV could contribute 86 % of the total electricity generated by 2050, which would represent about 83 % of the total final energy demand in that year.

From a technological perspective, in order to transition to a fully sustainable energy system, there are three vital elements: a high level of renewable electricity across all sectors, flexibility, and sustainable fuels production. And for a cost-optimal solution, there are three key enablers: solar PV technology, zonal (or regional) interconnection, and full sectoral integration or sector coupling. However, to ensure a truly sustainable energy transition and to reach a fully defossilised energy system, the energy policies acquire fundamental importance [147]. In this sense, in order to accelerate the transition towards a fully sustainable energy system in Chile, the recommendations for decision-makers are as follows:

- Increase the capacity of the transmission lines in the National Electric System by at least 50 %, particularly, the interconnection between the Atacama Desert and the central-south zones of the country.
- Implement fossil fuel bans across all sectors.
- Support and foment sector coupling and the PtX-based production of synthetic (gas and liquid) fuels and chemicals.
- Implement a regulatory change in the prosumer scheme and include a feed-in-tariff.
- Progressively increase the CO_2 emission taxes during the transition period in at least half of the values assumed in this study.
- Promote WACC lower than 7 % for RE projects.
- Support and foment the implementation of district heating and heat pumps in the prosumer segment.
- Facilitate and foment the implementation of new business models that include the communities and citizens.
- Estimate and consider the social heath saving cost, the creation of jobs and the GDP growth caused by the RE technologies in the energy transition analysis.

Furthermore, we conclude that it is much more important to go for a full defossilisation of the energy system across all sectors, rather than to reach carbon neutrality. In addition to this, it would imply pathways that will be consistent with the Paris agreement targets. The benefits of the solution for each country would go beyond just the environment. Actually, this would also allow them to reach a truly sustainable energy system in their three spheres, which could help us all reach a global post-fossil fuels economy.

Finally, the contribution that Chile could make to the global sustainable energy transition and to reaching a global post-fossil fuels economy, as well as the impact of this in the Chilean energy system structure is still an open question. In any case, Chile has the potential and the opportunity to contribute to the acceleration of both of these global goals, particularly through the supply of clean copper and lithium, and through sustainable RE-based fuel and chemical production.

Credit author statement

Juan Carlos Osorio-Aravena: Conceptualization, Methodology, Investigation, Writing – original draft preparation. Arman Aghahosseini: Methodology, Investigation, Visualization, Writing – original draft preparation. Dmitrii Bogdanov: Methodology, Investigation, Software, Writing – review & editing. Upeksha Caldera: Investigation, Writing – review & editing. Narges Ghorbani: Investigation. Theophilus Nii Odai Mensah: Investigation. Siavash Khalili: Investigation. Emilio Muñoz-Cerón: Investigation. Christian Breyer: Conceptualization, Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111557.

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