International Journal of
Sustainable Energy Planning and Management

Transition toward a fully renewable-based energy system in Chile by 2050 across power, heat, transport and desalination sectors

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ABSTRACT

Renewable energies will play a significant role in transitioning towards sustainable energy system in order to match the goal under the Paris Agreement. However, to achieve this goal, it will be necessary to find the best country pathway, with global repercussions. This study reveals that an energy system based on 100% renewable resources in Chile would be technically feasible and even more cost-efficient than the current system. The Chilean energy system transition would imply a high level of direct and indirect electrification across all sectors. Simulation results using the LUT Energy System Transition model comprising 108 technology components show that the primary electricity demand would rise from 31 TWh to 231 TWh by 2050, which represents about 78% of the total primary energy demand. The remaining 22% would be composed of renewable heat and bioenergy fuels. Renewable electricity will mainly come from solar PV and wind energy technologies. Solar PV and wind energy installed capacities across all sectors would increase from 1.1 GW and 0.8 GW in 2015 to 43.6 GW and 24.8 GW by 2050, respectively. In consequence, the levelized cost of energy will reduce by about 25%. Moreover, the Chilean energy system in 2050 would emit zero greenhouse gases. Additionally, Chile would become a country free of energy imports.

Keywords:

100% renewable energy;
Sustainable energy transition;
Energy system modeling;
Energy planning;

URL: http://doi.org/10.5278/ijsepm.3385

1. Introduction

Chile is highly dependent on fossil fuels for energy production. In 2017, the share was around 68% of the total primary energy supply [1]. The energy sector has been responsible for major greenhouse gas (GHG) emissions in the country, representing about 77% of the total [2]. According to Climate Action Tracker [3], Chile has been classified as a highly insufficient country in terms of contribution to the Paris Agreement targets based on current policies.

On the other hand, according to the Climatescope report by BNEF [4], Chile has become a world leader in the emerging markets for using and enabling sustainable energy. This report shows that the country rose from the seventh position in 2017 to the first place in the ranking in 2018, which has occurred mainly due to the implementation of public policies and investments in renewable energy (RE). This South American nation is known for enormous RE potential, especially for solar and wind energy. Nowadays, it is highly competitive to produce electricity from these resources in Chile, without subsidies [5].

Moreover, Chile is the first country in the region with a geothermal power plant (PP) and soon will be the first to have a concentrating solar thermal PP which will provide electricity 24 hours a day. Chile has excellent conditions to

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Abbreviations

A-CAES	Adiabatic compressed air energy storage
CAPEX	Capital expenditures
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
CSP	Concentrated solar thermal power
DAC	CO_2 Direct air capture
DH	District heating
GHG	Greenhouse gas
GT	Gas turbine
HDV	Heavy duty vehicle
HT	High temperature
ICE	Internal combustion engine
IH	Individual heating
LDV	Light duty vehicle
LNG	Liquefied natural gas
LUT	Lappeenranta University of Technology
MDV	Medium duty vehicle
OCGT	Open cycle gas turbine
OECD	Organization for Economic Co-operation and Development
OPEX	Operational expenditures
PHES	Pumped hydro energy storage
PP	Power plant
PtG	Power-to-gas
PtH	Power-to-heat
PV	Photovoltaic
RE	Renewable Energy
SF	Solar field
ST	Steam turbine
TES	Thermal energy storage
TTW	Tank-to-wheel
2W	two-wheelers
3W	three-wheelers
€	Euro

transform rapidly its existing energy system, towards a sustainable one independent of fossil fuels.

The deployment of RE technologies in Chile has advanced faster than planned. In December 2018, their contribution to electricity generation exceeded 3 times the mandatory target set by government laws, not including hydropower plants more than 20 MW [6]. At the end of 2018, RE technologies reached 20.8% of the total installed capacity in the country [6]. If larger hydropower plants are included (>20 MW), this percentage increases up to 47.0% [6].

However, the total GHG emissions in the energy sector has not been reduced [7]. Therefore, it is necessary to increase the current goal in order to meet the set international climate targets. Although Chile's Energy Ministry has a long-term energy planning [8], it is not contemplating an energy system based on 100% RE for all sectors. Previous work on energy system analysis for a fully renewable based system in Chile [9,10] has been carried out for the power sector only. To our knowledge, no scientific articles exist which discuss a system based on 100% RE to this country for all its energy sectors. However, 100% RE supply is an emerging topic of high interest at various levels, from household [11], to district [12], to national [13], to regional [14], to continental [15] and global [16] and in practically all parts of the Americas [15] as well.

One of the most important action, to comply with the Paris Agreement is to attain an energy system with high levels of sustainability, country by country. Hence, this study has the purpose of modeling a transition in Chile toward a fully sustainable energy system across all sectors. This was done to define an energy scenario that achieves the defined climate target at the country level. The principal aim is to acquire objective information on this new system paradigm, in particular on the technical feasibility and the economic viability, and estimates on environmental benefits. These results would be helpful and act as an example to other countries in the region, with similar conditions.

2. Methods and data

The LUT Energy System Transition model [16–18] was utilized to study the Chilean energy transition. It simulates an energy system, integrating all key aspects of the power, heat, transport, and desalination sectors. The model works with linear optimization under given constraints, in full hourly resolution for an entire year, and applies cost-optimal simulations. The historic weather year data for 2005 has been used as explained more in Bogdanov et al. [16]. The aim of the model is to apply a scenario for an energy system based on 100% RE to be achieved at the end of the transition period from 2015 until 2050. The target of the objective function is to achieve a least cost energy system for given constraints and in full hourly resolution for all hours of an entire year. The modeling tool models the energy system transition in five-year time steps, from 2015 to 2050.

Figure 1 shows the general process flow of the LUT Energy System Transition model. A description of the model can be found in Bogdanov et al. [16] for power sector only and more details in Ram et al. [17] for power, heat, transport and desalination sectors. The specific sector coupling of the integrated power and heat sectors is described in detail in Bogdanov et al. [18] (see Figure 2).

The following paragraphs describe how the data preparation as an input for the modeling set up was carried out. Then, a brief explanation is given on the key aspects of the model.

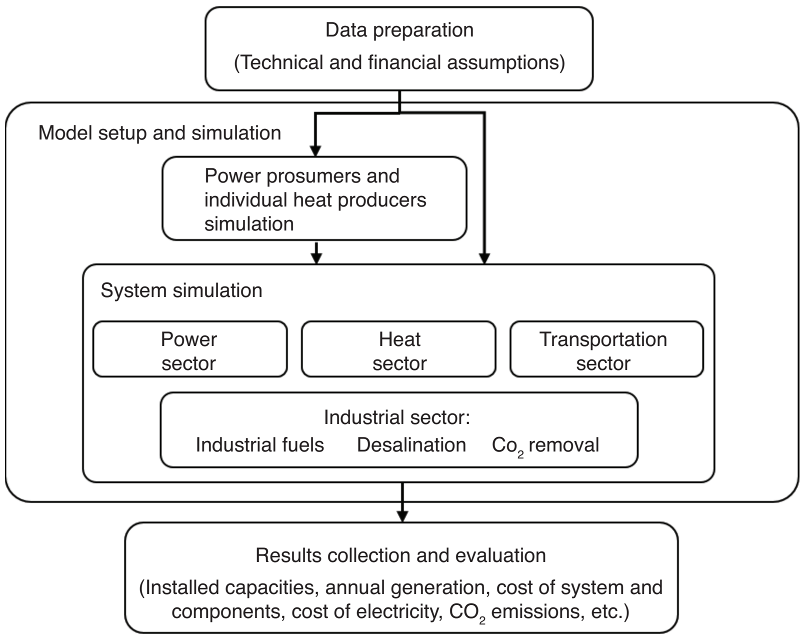

Figure 1: Fundamental structure of the LUT Energy System Transition model [16,17]

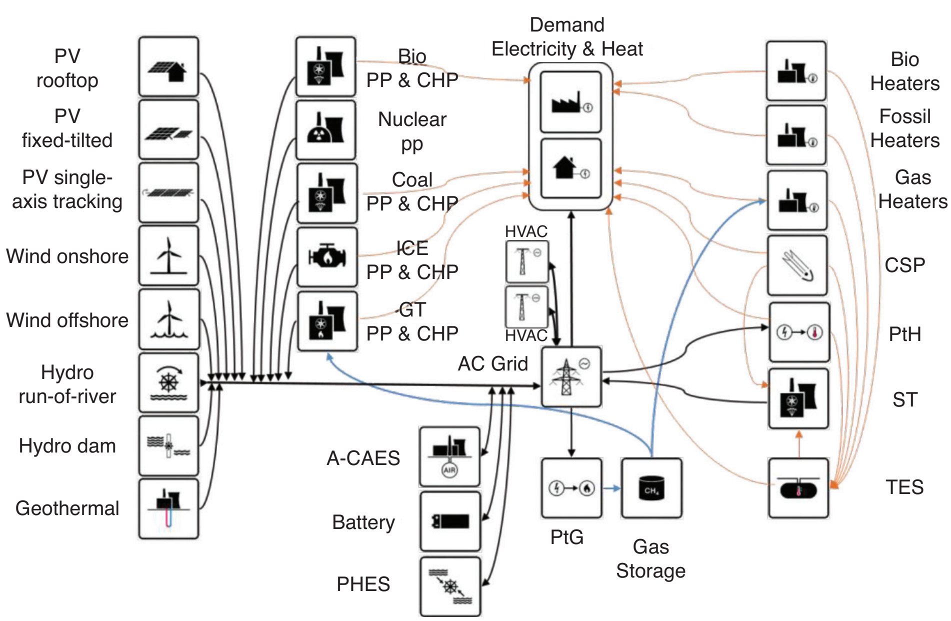

Figure 2: Schematic of the LUT Energy System Transition model for power and heat sectors [18]

As a first step, data collection related to the Chilean energy system was carried out. Here, hourly demand profiles for the different energy sectors were also generated. It was based on the methodology of Toktarova et al. [19] in order to generate the synthetic electricity load profiles from 2015 to 2050. Then, using as the initial point the existing energy system in 2015 without non-energy uses [20], long-term total final energy demand by energy forms and sectors was determined (see Figure 3). The final energy demand, which comprises electricity, heat and fuel, had an average annual growth rate of 0.5% during the transition period. This growth is a result of different average annual growth rates assumed for the final energy demand by sector involved (power, heat, transport, and desalination) where population growth and technological changes are also included.

Power demand was divided into residential, commercial (public included) and industrial end-users. Heat demand was categorized into four types of end-consumption: space heating, domestic hot water heating, industrial process heat, and biomass for cooking. In addition, heat demand was classified as low, medium, and high temperatures.

For the case of the transport sector, transportation demand was divided according to Breyer et al. [21] and Khalili et al. [22] into the following modes: road, rail, marine, and aviation, each one for passenger and freight transportation. The road segment was subdivided into passenger light-duty vehicles, passenger 2-wheelers/3-wheelers, passenger bus, freight medium-duty vehicles, and freight heavy-duty vehicles. This demand was estimated in passenger-kilometers for passenger transportation and in ton-kilometers for freight transportation. Then, this demand was converted into final transport energy demand based on the specific energy demand by mode and type of vehicle technology [21]. Smart charging of battery-electric vehicles and Vehicle-to-Grid flexibility is not considered in this study, but the possible energy system impact is discussed by Child et al. [23].

The desalination demand was projected in those zones with a water stress index greater than 40%, as a function of the water stress index and the total projected water demand for specific years during the transition period, according to Caldera et al. [24,25]. The total water demand includes the projected demand from the municipal, industrial (included mining) and agricultural sectors.

Details of these assumptions sector-wise are presented in the Supplementary Material (Tables S1-S7 and Figures S1-S12).

Within the data preparation, the resource potentials of various RE technologies throughout the country were estimated. Real weather data was used for assessing the solar, wind and hydro resources [26,27,28]. The potentials for biomass and waste resources were classified into biogas/solid residues and solid wastes, based on Bunzel et. al. [29]. In addition, geothermal energy potential was estimated, according to Gulagi et al. [30].

Additionally, the financial and technical assumptions for all technologies involved in the modelling were obtained from different sources, and are presented in the Supplementary Material (Tables S8-S10). They include the learning curves of all key technologies which were considered to have a direct or indirect impact on future costs since they are a crucial element for determining a cost-optimal energy transition route.

Simulations were then carried out using the modelling setup of LUT Energy System Transition model. In

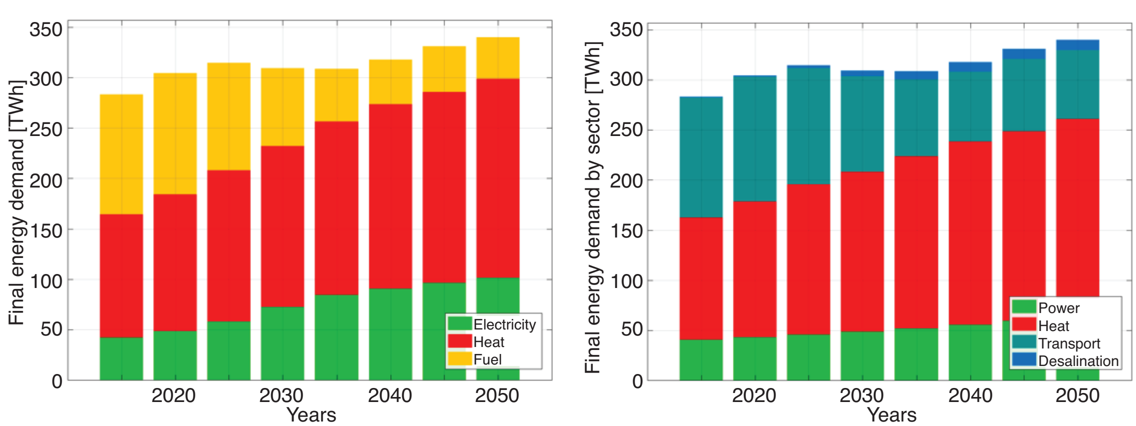

Figure 3: Final energy demand by energy form (left) and by sector (right) during the energy transition from 2015 to 2050

essence, the tool included all critical aspects of the power, heat, transport, and desalination sectors. Here, 108 energy technologies throughout the different sectors were integrated. In the first step, the prosumer, energy consumers that can produce their own energy and sell the excess, simulations determined a cost-effective share of both power and heat prosumers through the transition period in order to evaluate a more decentralized and distributed energy system.

The main objective of the simulation for the transition period was to create a fully sustainable energy system, as defined in Child et al. [31], for Chile while simultaneously reducing the GHG emissions to zero by 2050 and attaining energy independence, while understanding the respective economics.

3. Results

The results are presented under the following structure: Section 3.1 highlights the fundamental trends throughout the transition towards a fully sustainable energy system in Chile by 2050. The findings on electricity supply and energy storage across all integrated sectors are pointed out in Section 3.2. The results for power and heat, transport and desalination sectors are shown in Section 3.3, Section 3.4 and Section 3.5, respectively, while for the energy system cost and the GHG emission reduction are presented in Sections 3.6 and 3.7, both related to an energy transition in Chile towards a system based on 100% RE by 2050.

3.1. Fundamental trends in the energy system

Figure 4 (top left) shows the results of the primary energy demand by sector through the transition from 2015 to 2050. According to this bar-graph, the share of primary energy demand by sector does not vary significantly during the transition. The desalination sector will be an exception due to the rising water stress projected in the coming decades.

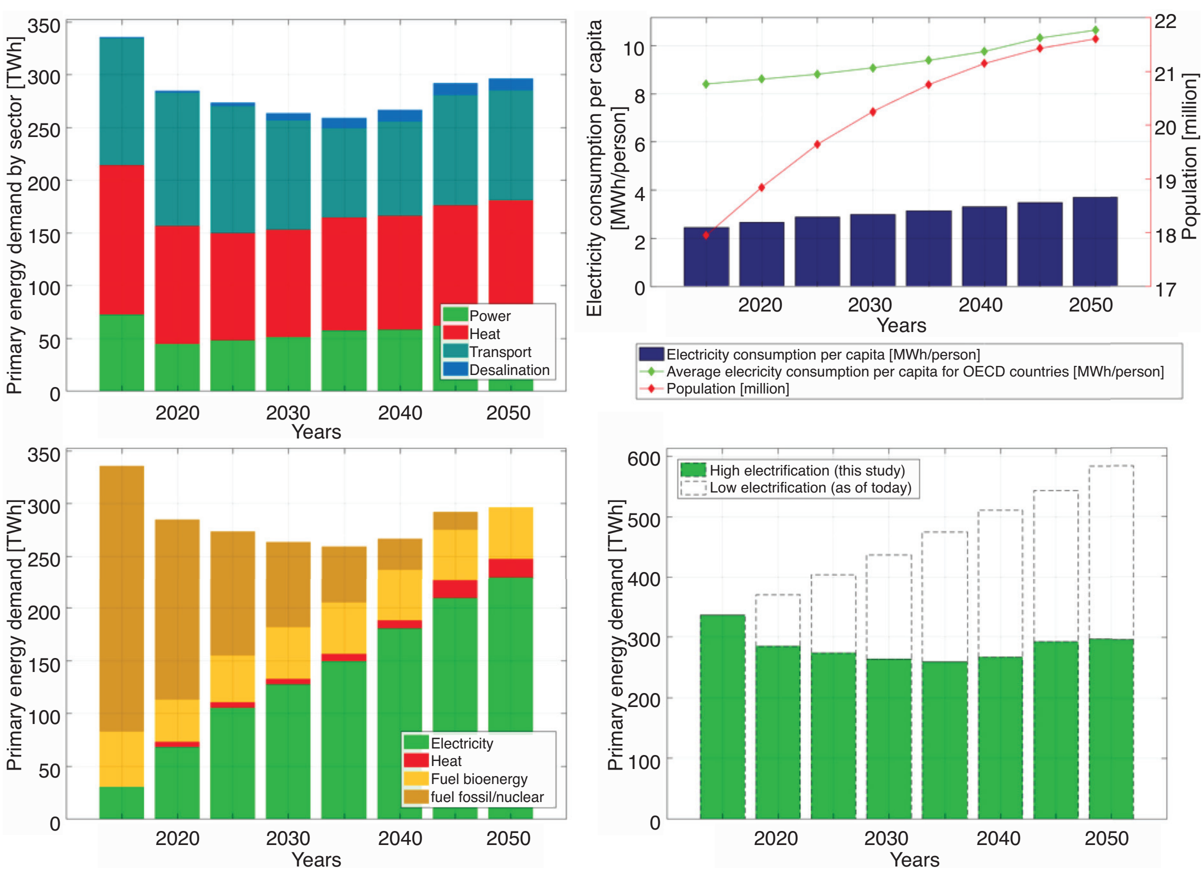

Figure 4: Primary energy demand sector-wise (top left), electricity consumption per capita with population (top right), primary energy demand by energy form (bottom left), and efficiency gain in primary energy demand (bottom right) through the transition

Another result that we can observe in Figure 4 (top left) is that the total primary energy demand by 2050 will be less than in 2015, although the population will increase from 17.9 million to 21.6 million [32] during the transition period (see Figure 4, top right), even assuming a sustainable economic growth. This will be an outcome of a more efficient energy system based on renewable resources and technological changes. As Figure 4 shows (top right), the electricity consumption per capita in Chile will increase at a rate that is similar to the average of the OECD countries until 2050, but almost 4 times less in terms of per capita.

The modeling results reveal massive electrification through the energy transition period for Chile. Of the total 300 TWh of primary energy demand in the year 2050, about 78% would be supplied by renewable electricity technologies. Primary renewable electricity would have a sustained growth from 31.1 TWh by 2015 to 231 TWh by 2050, (see Figure 4, bottom left) and the rest of about 50 TWh and 15 TWh of primary energy demand would come from bioenergy fuels and heat produced based on renewable resources, respectively.

As can be seen in Figure 4 (bottom right), high levels of direct and indirect electrification, resulting from renewable energy technologies, would create a much more energy-efficient system if we compare it with an energy system based on current practices. An energy transition scenario with high share of renewable electricity could be about 90% more efficient than another with low electrification levels.

3.2. Electricity supply and energy storage across all sectors

The electricity generation from different technologies to cover the Chilean demand of power, heat, transport and desalination sectors during the energy transition is shown in Figure 5 (top). The major contribution of electricity generation across all sectors in 2050 would come from wind onshore (50%), followed by solar photovoltaic

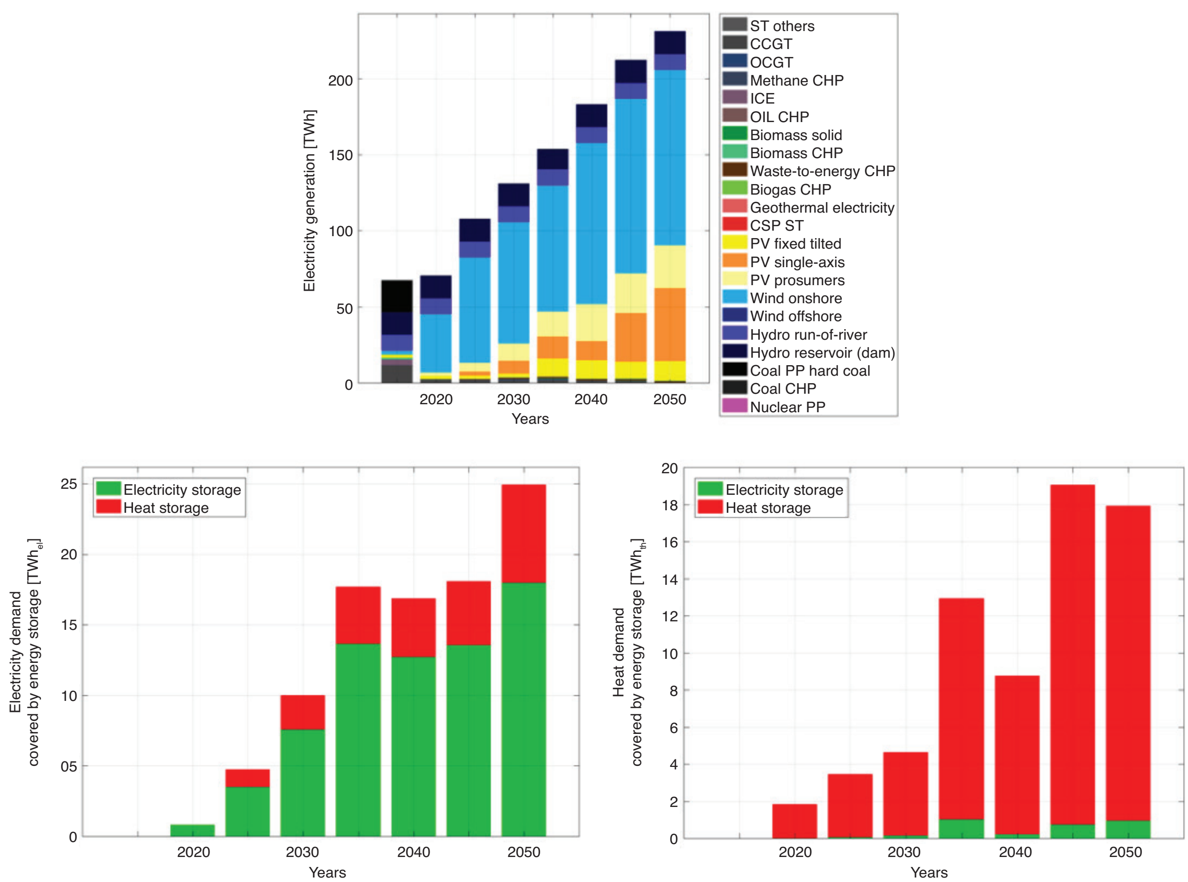

Figure 5: Technology-wise electricity generation (top), electricity demand covered by energy storage (bottom left), and heat demand covered by energy storage (bottom right) during the energy transition from 2015 to 2050

(PV) (39%), and the remaining 11% from hydropower with minor contributions of concentrated solar thermal power (CSP), biomass, and geothermal PP. Solar PV prosumers would supply about 12% of the total electricity generation needed by 2050. By this year, the total renewable installed capacity required to generate electricity across all sectors would rise to about 81 GW; 54% for power and heat, 40% for transport, and 6% for desalination. New installed capacity by sector in 5-years intervals is presented in the Supplementary Material (Figures S20-S25).

Energy storage technologies will also be needed to support the supply of the final electricity and heat demand from all sectors. Figure 5 (bottom left and right) shows the electricity and heat demand covered by energy storage through the transition. Electricity and heat storage output will rise to about 25 TWh_{el} and 18 TWh_{th} by 2050. These values represent 25% and 9% of the final electricity and heat demand in that year, respectively. Electrical and thermal storage technologies would support the supply to over 14% of the total final energy demand from all sectors by 2050.

3.3. Power and heat sectors

Figure 6 shows the results for the installed capacities according to different technologies needed to generate electricity and heat for the power and heat sectors through the transition. The total installed power generation capacity increases from 21.2 GW in 2015 to 47.3 GW by 2050, from which 32.7 GW correspond to solar PV and wind technologies. The PV prosumers' installed capacity would be 31% of the total capacity. In the same year, PV single-axis and wind onshore technology would reach 20% and 19% of the total installed capacity for power and heat sectors, respectively (see Figure 6 left). From Figure 6 (right), one can see that solid-biomass technologies will be necessary to supply heat demand in the heat sector through the whole transition period.

Electricity and heat generation for power and heat sectors from 2015 to 2050 are shown in Figure 7. As is illustrated in Figure 7 (left), the wind onshore electricity generation will be dominating from 2020 to 2040. Solar PV prosumers would significantly increase through that period contributing about 24% of the electricity generation for power and heat sectors by 2050 (see Figure 7 left). In the same year, PV single-axis would contribute to nearly 17% of the electricity generation.

From Figure 7 (right), one can see that heat pumps for individual heating (IH) would play a significant role through the transition, having a share of about 50% of heat generation by 2050. The remaining heat generation will come from biomass-based technologies (24%), and direct electric heating (15%), with nearly 9% from solar thermal, and a small part of synthetic natural gas produced from renewable electricity that will replace remaining fossil gas. Therefore, heat pumps for IH and district heating (DH) will be the key for covering the heat demand during the transition period, which can be supplied by renewable electricity.

Energy storage will be important as it supports the solar PV and wind power generation systems. The installed electricity storage capacity increases from nearly 0.01 TWh in 2025 to over 0.07 TWh by 2050. As indicated in Figure 8 (left), batteries for PV prosumers will start to emerge in 2025 and both battery storage for PP and adiabatic compressed air energy storage (A-CAES) would start to appear in the interval between 2030–2035.

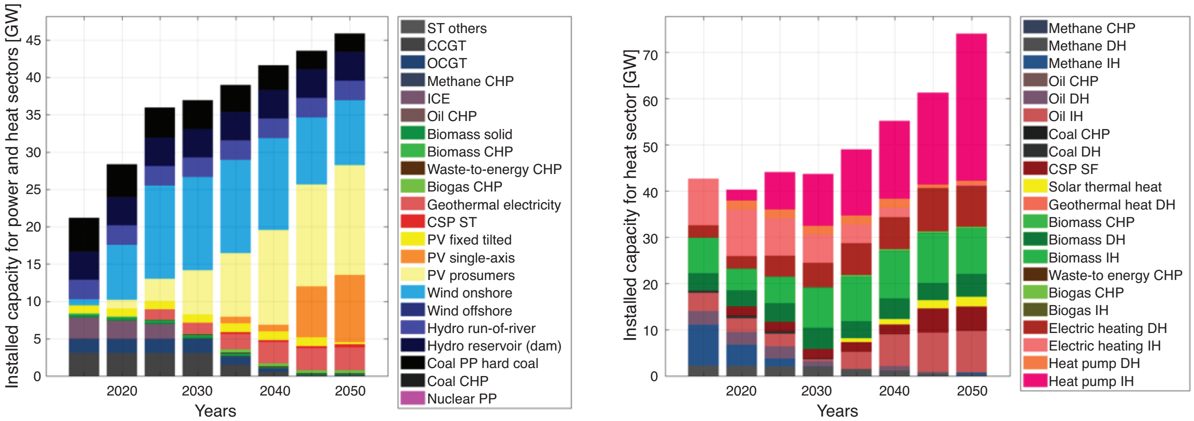

Figure 6: Power and heat - Installed capacity by power technology (left) and installed capacity by heat technology (right)

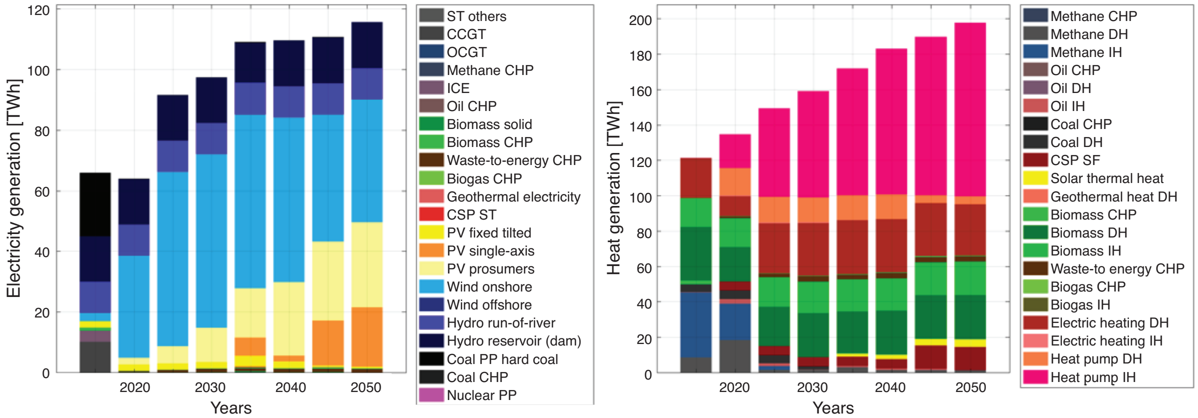

Figure 7: Power and heat - Electricity generation by power technology (left) and heat generation by heat technology (right)

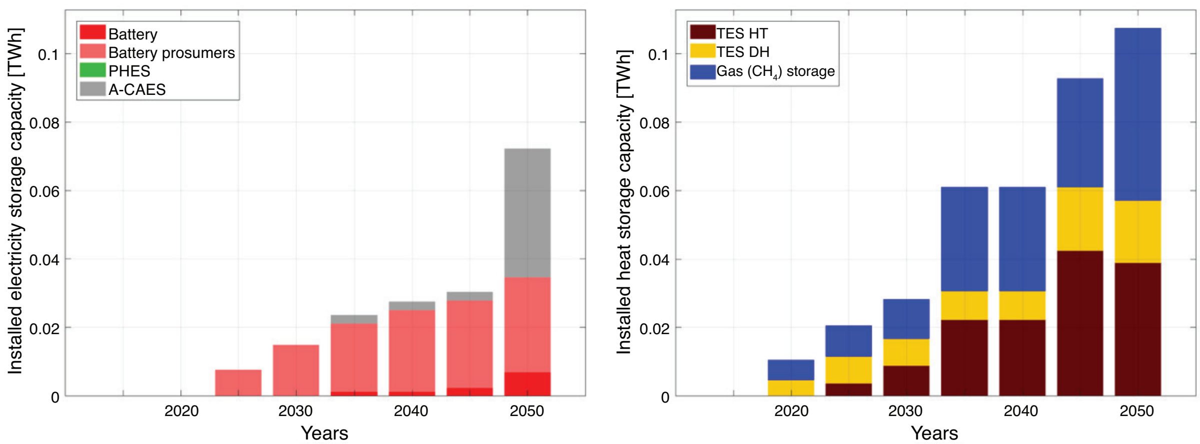

Figure 8: Power and heat - Installed electricity storage capacities (left) and heat storage capacities (right)

Utility-scale and PV prosumer batteries will be the major contributors in the electricity storage output with 13.4 TWh_{el} of the 15.5 TWh_{el} by 2050 (see Figure 9 left).

Moreover, thermal energy storage (TES) technologies will also be necessary to enable the transition of the power and heat sectors. Figure 8 (right) shows the increase of the installed heat storage capacity from 2015 to 2050, which would reach about 0.11 TWh by 2050. Both TES high temperature (HT) and DH will dominate the heat storage output through the transition period, reaching a total of about 15.3 TWh_{th} by 2050 (see Figure 9 right).

3.4. Transport sector

Figure 10 shows the final energy demand and electricity demand to achieve sustainable transportation in Chile by 2050. As can be seen on the left, after an initial increase, the final transport energy demand will decline from 125 TWh in 2020 to 68.4 TWh by 2050, mainly due to the efficiency gains caused by direct and indirect electrification of the sector (see Figure 10 right).

The final energy demand for sustainable transport by 2050 would be covered by direct electricity (40%), followed by synthetic fuels (liquid and gas) (34%) and hydrogen (26%). The transport sector would experience a transformation to a combination of electric vehicles with batteries, plug-in hybrids, and fuel cells, whereas the marine and aviation demand would be mainly covered by synthetic fuels and hydrogen from low-cost electricity. The results to cover the energy demand for transportation by mode, segment, type of vehicle, and sustainable fuels production can be seen in the Supplementary Material (Tables S18-S21 and Figures S26-S27).

The results reveal that to attain sustainable transport, it will be necessary a substantial increase in the installed power generation capacity through the transition to around 33.2 GW by 2050. As can be seen in Figure 11,

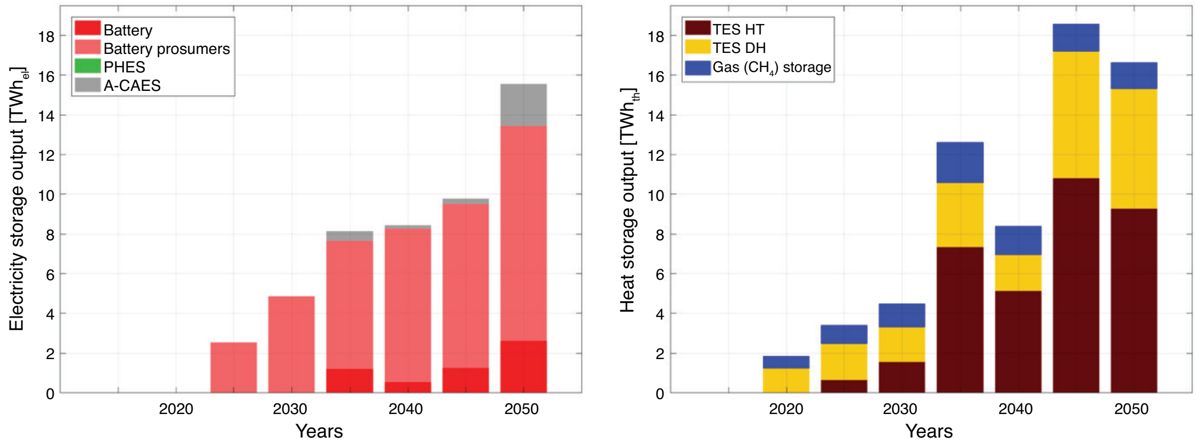

Figure 9: Power and heat - Electricity storage output (left) and heat storage output (right)

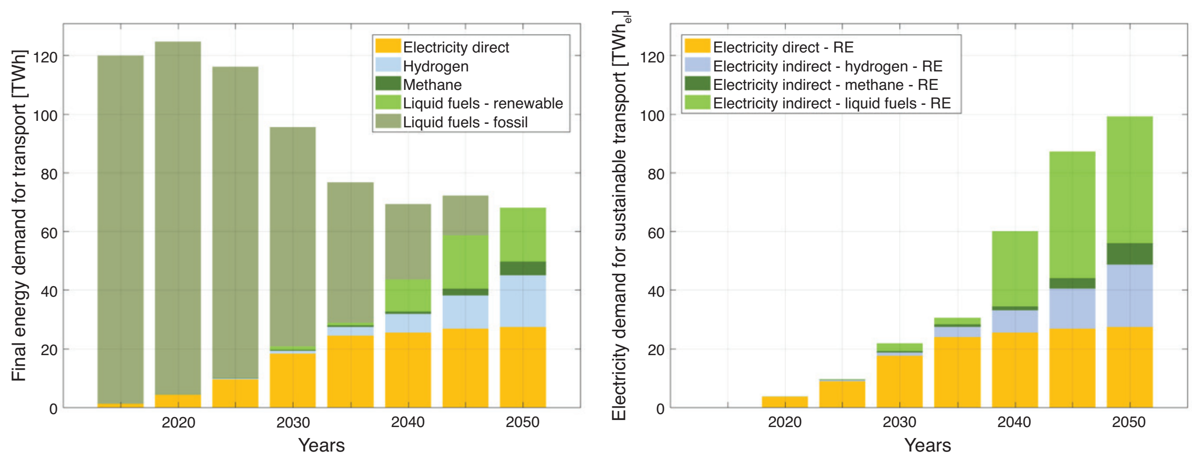

Figure 10: Final transport energy demand by fuel form (left) and electricity demand for sustainable transport (right)

solar PV and wind technologies would be predominant from 2020, reaching a total of 16.5 GW and 14.9 GW by 2050, respectively.

The renewable installed capacity for direct electrification and to produce sustainable fuels (hydrogen, liquid, and renewable gas) would rise at an average annual growth rate of 9.3% (see Figure 11 left). This also includes the installed capacity for CO_2 direct air capture technologies [33], which are used to produce some of the sustainable fuels. As is indicated in Figure 11 (right), renewable electricity generation will dominate from 2020 onwards. In 2050, nearly 66% of electricity generation would come from wind onshore complemented by PV single-axis tracking (27%) and PV fixed tilted power plants (7%). The production of sustainable fuels for transportation demand could be fully based on renewable electricity from 2040 onwards.

Electricity storage technologies will be a critical aspect to complement the electrification of the transport sector. Figure 12 (left) shows that the installed capacities of electricity storage will reach its peak by 2035, while keeping it constant until 2050. Most of the installed storage capacities are A-CAES and utility-scale batteries. In the case of electricity storage output (see Figure 12 right), after a rapid increase to 9 TWh_{el} by 2035 it would decline and maintain between 6-7 TWh_{el} till 2050. In that period, the low electricity storage of less than 7% of generated electricity for the transport sector is enabled by the flexible operation of batteries, water electrolyzer units, and hydrogen buffer storage for synthetic fuel production.

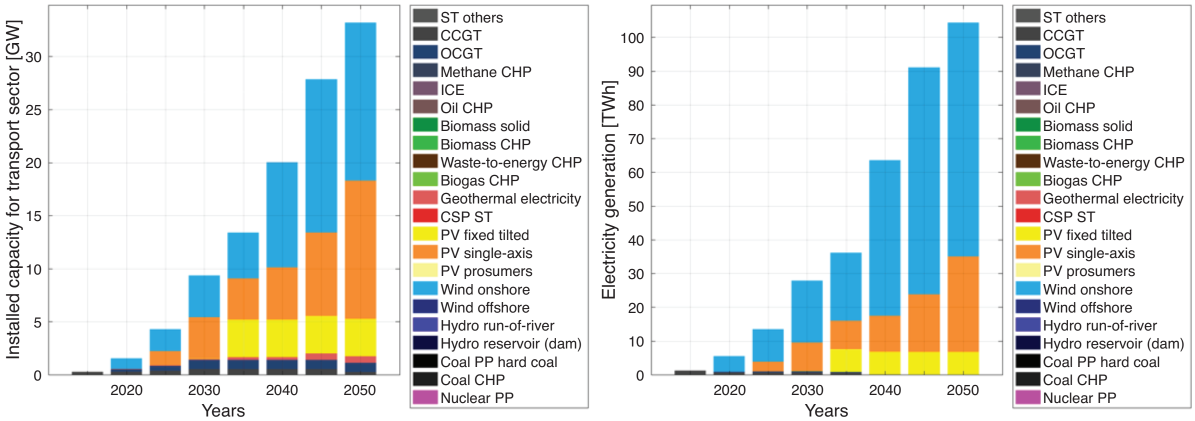

Figure 11: Transport - Installed capacity by power technology (left) and electricity generation by power technology (right)

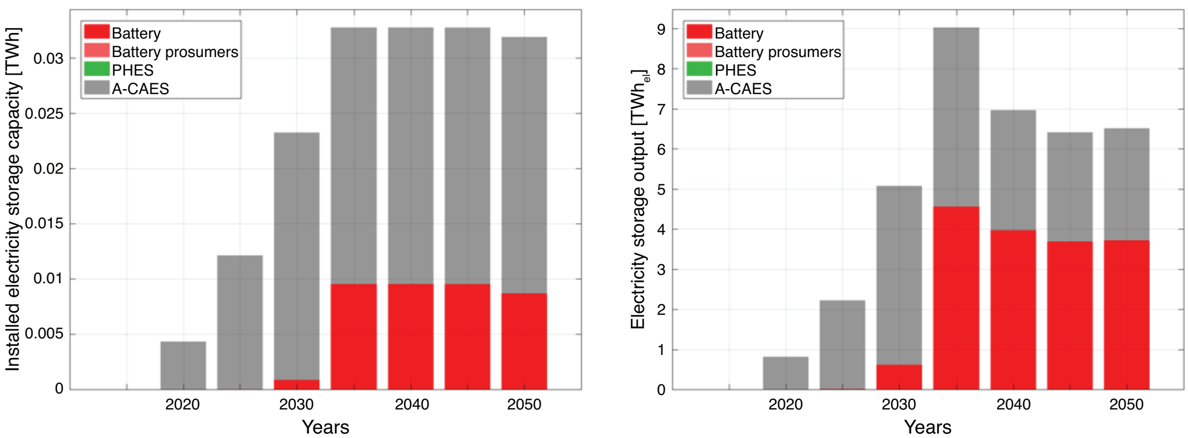

Figure 12: Transport - Installed electricity storage capacities (left) and electricity storage output (right)

3.5. Desalination sector

Desalination demand will increase during the transition period due to the rising water stress that is expected globally. The results show that it would be required to increase the renewable installed capacity from 0.03 GW in 2020 to 5.19 GW by 2050 (see Figure 13 left). Here, solar PV and wind technologies would reach 58% and 23% of that installed capacity. Energy demand for water desalination can be fully supplied from renewable electricity by 2050. In that year, solar PV and wind technologies could contribute 51% and 49% of the electricity generation, respectively (see Figure 13 right).

Energy storage technologies will also be needed for the desalination sector since using batteries for raising the full-load hours of the desalination plants is cheaper than investing in more desalination capacities and buffering the clean water in water storage [34]. As can be seen in Figure 14 (left), the installed capacity of energy storage technologies would occur mainly from 2035. Figure 14 (right) shows that utility-scale batteries would be the main contributing technology for storage output. In 2050, output from batteries will cover 28% of the 10.2 TWh demand from desalination (for more details of these results, see Tables S22-S23 in the Supplementary Material).

3.6. Energy costs and investments

A high level of renewable electricity implies a most cost-efficient energy system across all sectors combined. From the economic point of view, the total annual cost in a fully sustainable energy system will be cheaper in the year 2050 (12.5 b€) than the present one (16.3 b€) (see Figure 15, left). As depicted in Figure 15 (right), capital expenditure (CAPEX) will increase during the

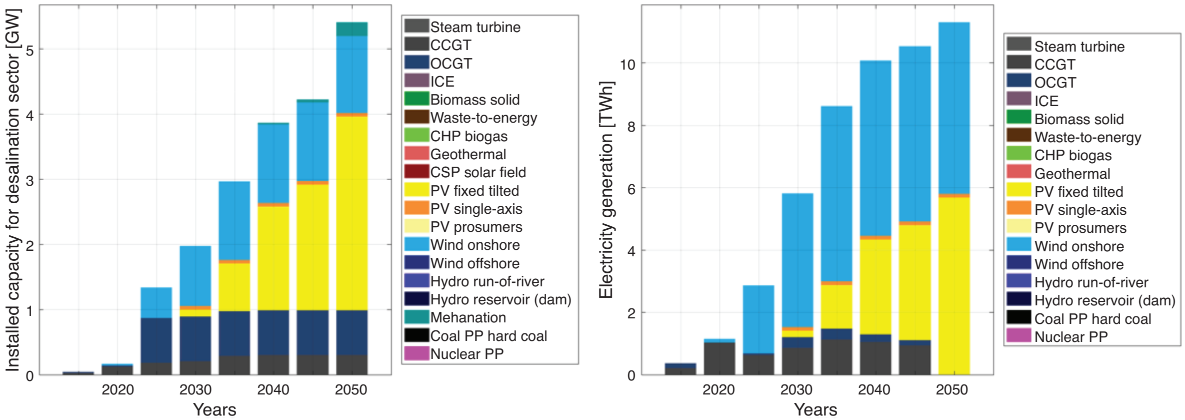

Figure 13: Desalination - Installed capacity by power technology (left) and electricity generation by power technology (right)

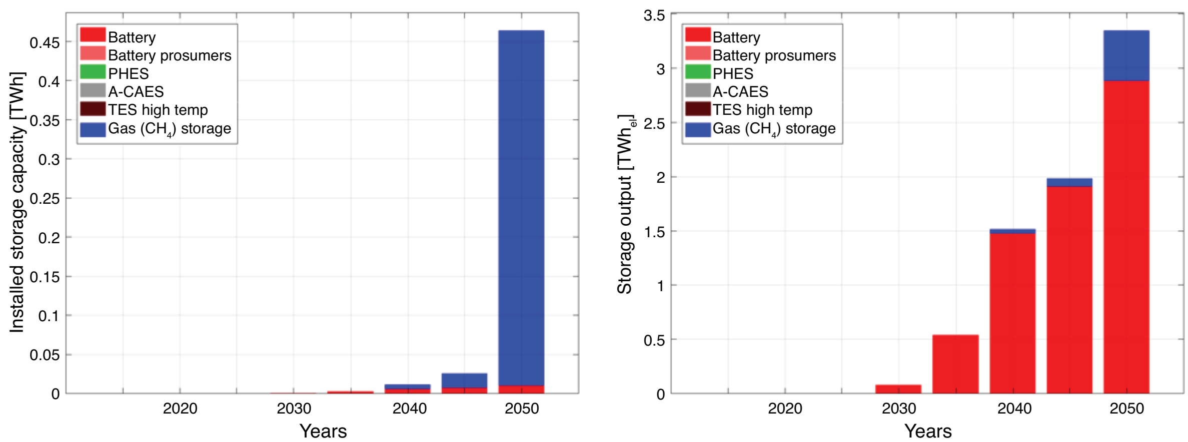

Figure 14: Desalination - Installed storage capacities (left) and storage output (right)

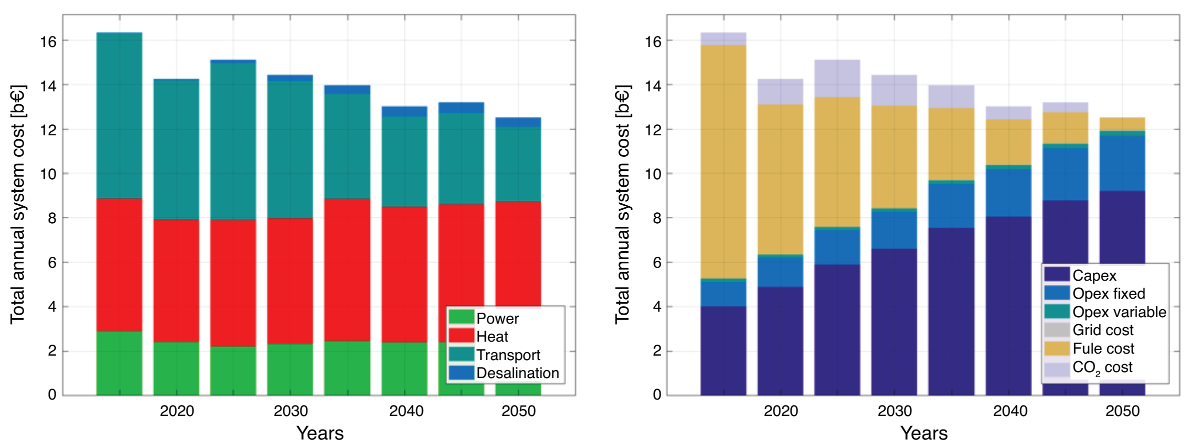

Figure 15: Annual system costs, sector-wise (left) and main cost category (right) through the transition

transition period, while fuel costs continue to decline. The constant increase in CAPEX-related energy system costs indicates that fuel imports will fade out through the transition. This would lead to energy independence and energy security since the Chilean energy system will be based mainly on local solar and wind resources.

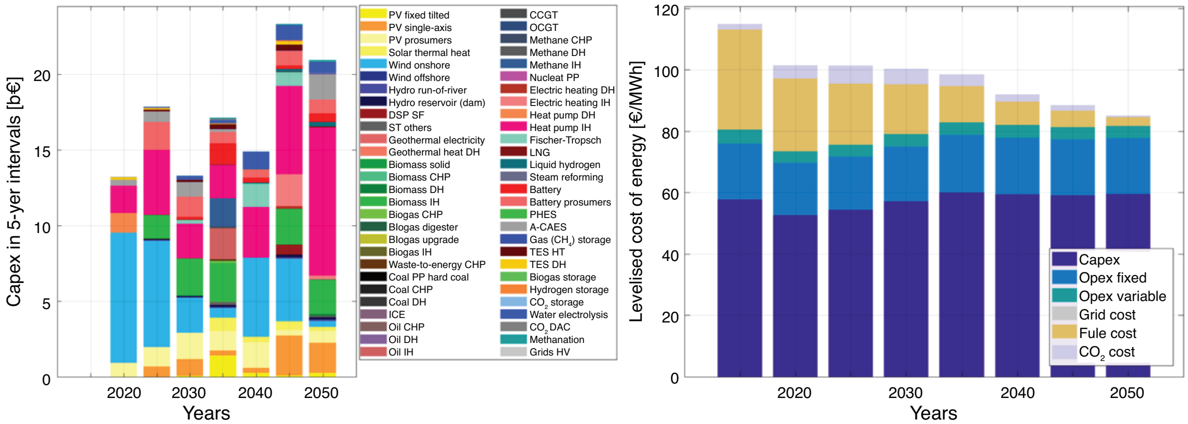

Figure 16: Capital expenditure for five-year intervals (left) and levelized cost of energy (right) through the transition

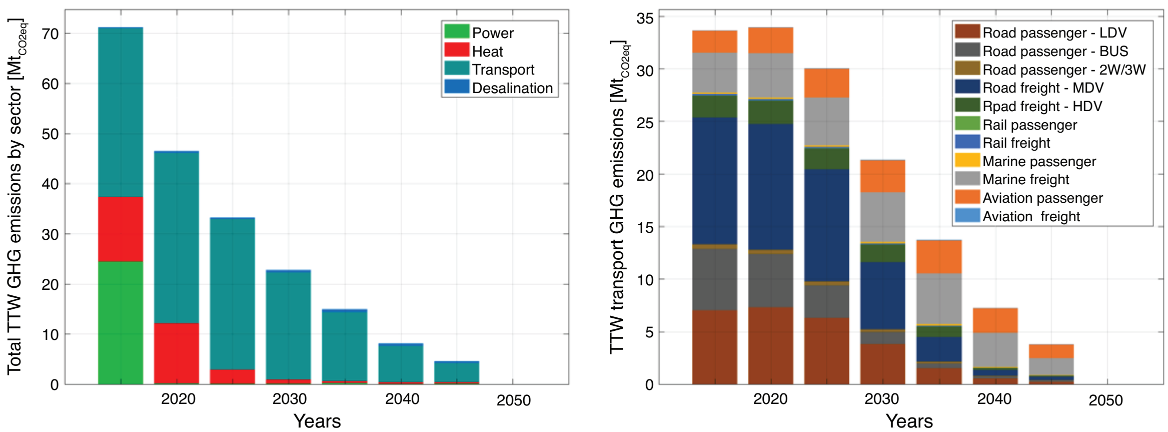

Figure 17: Sector-wise GHG emissions (left) and GHG emissions in the transport sector by mode and segment (right), during energy transition from 2015 to 2050

The installed capacity of solar PV and wind technologies would increase significantly during the transition across all sectors since these power generation sources will become the least cost options in Chile. Notwithstanding, as is illustrated in Figure 16 (left), CAPEX will be distributed across a range of technologies with large investments for solar PV, wind energy, heat pumps, batteries, and synthetic fuel conversion, especially in the second half of the energy transition period. However, as can be seen in Figure 16 (right), the levelized cost of energy for the full system would be reduced through the transition from about 114 in 2015 to 85 €/MWh by 2050. This will be possible thanks to the low cost of generating electricity from solar PV and wind onshore PP. The electricity generation cost of these technologies will decline from 50 €/MWh and 39 €/MWh in 2015 to 13 €/MWh and 20 €/MWh by 2050, respectively.

All of the energy cost and investment results by sector and fuel costs through the transition period are available in the Supplementary Material (Tables S24-S27 and Figures S28-S38).

3.7. Greenhouse gas emissions reduction

One of the most important consequences relates to (energy) GHG emissions: an energy system based on 100% RE by 2050 will imply a full defossilization by 2050. As is indicated in Figure 17 (left), the GHG emissions of the whole Chilean energy system, all sectors involved, can decline from approximately 70 $MtCO_{2eq}$ in 2015 to zero by 2050. In Figure 17 (left) it can be also appreciated that GHG emissions related to the power and heat sectors could be drastically reduced by 2030. Nevertheless, GHG emissions from the transport sector will decline in a slow manner, as shown in Figure 17 (right). All of this will mainly be possible thanks to high levels of renewable electricity supply across the power, heat, transport, and desalination sectors.

In summary, the simulation results to attain a fully sustainable energy system across the power, heat, transport, and desalination sectors in Chile by 2050 show that a transition toward a 100% RE energy system for Chile would be technically feasible and economically viable, based on the input data considered. The energy supply would come from local and distributed renewable resources. Consequently, it implies that the Chilean energy system could reduce its direct GHG emissions to zero by 2050, while at the same time gaining energy independence.

4. Discussion

This section is composed of three parts. Firstly, the overall findings are discussed based on previous works (Section 4.1). Secondly, in Section 4.2 the limitations of this study are pointed out. Thirdly, in Section 4.3 recommendations for future research in Chile are given as well as suggestions for the next studies in the sustainable energy transition field.

4.1. Overall findings

This study illustrates that to achieve a Chilean energy system based on 100% RE by 2050 is economically and technically possible. The results for Chile's energy transition, across the sectors of power, heat, transport and desalination, are first of its kind.

Previous studies applied to this country to attain a fully RE system [9,10] and at least 60% of the electricity generated from RE sources [35,36,37] have been conducted to cover most of the demand from the power sector. All of them show significant contributions from solar PV and wind power, which is roughly in line with the results of this research and with the earlier findings for Chile in an integrated study for South and Central America [38]. Even more supportive of the findings of this study, Haas et al. [9,10] and Maximov et al. [37] highlight the nexus between solar PV, wind energy, and storage technologies to attain a RE-based power system.

In the case of the transport sector, Girard et al. [39] have recently presented some environmental and financial findings related to solar electricity production and electrical vehicle conversion in Chile, but this study is only applied to taxis (public transport cars), in the light-duty vehicle (LDV) road segment.

According to Chile's government, in his Long-term Energy Planning report [8], a study which includes all energy sectors, the best scenario shows that about 78% of the electricity generated would come from RE technologies by 2046. However, those almost 143 TWh of renewable electricity plus 64 TWh of biomass (firewood) would supply about 41% of the final energy demand by 2046.

Therefore, our results provide the first approximation in improving the present insufficient climate goals for Chile, based on a fully sustainable energy system, that is technically feasible and more cost-efficient. Moreover, it would imply a full defossilization of the Chilean energy system across all sectors by 2050. In addition, these results could lead Chile to focus on a more decentralized and independent country, in terms of energy. Actually, high RE supply is being discussed for practically all regions in the world [40], and 100% RE supply is technically feasible and economically viable as pointed out by Brown et al. [41].

The main sources for the energy supply in Chile are solar and wind energy, not surprising, since the best solar wind sites in the world are in the Atacama Desert [42] and Patagonia [43], respectively. The share of installed capacity needed for all sectors by 2050 will be composed of 50% solar PV, 28% wind power and 21% others. In the same year, the contribution to the electricity generation across all sectors would be of 50% wind power, 39% solar PV and 11% others. These findings have some differences with results from global studies to achieve the targets of the Paris Agreement based on 100% RE scenarios, which include all energy sectors as well.

According to Teske et al. [44], their results for Chile in the +1.5 ºC scenario by 2050 suggest a power generation structure composed of 33% variable RE (mainly solar PV and wind), 47% dispatchable RE (mainly hydropower) and 19% dispatchable fossil, whereas the latter seems not to be used with fossil fuels in 2050 but renewable options, as indicated in the same reference. In the case of Jacobson et al. [45], in 2050, Chile's all-purpose end-user load would be met with 34% (wind energy), 39% (solar PV) and 27% (others). These differences can be attributed to the methodological approach and assumptions. Nevertheless, there is something in well-consensus: nuclear PP is not an option in a sustainable energy system, mainly due to the reasons cautioned by Jacobson [46], which are very high economic cost, remaining risk of failures with fatal consequences and not resolved radioactive waste disposal, among others.

4.2. Limitations

One of the main limitations of these first results for Chile is that the total final energy demand of the country was considered as concentrated within one compact geographic node. This means that the energy demand from all sectors involved was not allocated at specific points of the country and assumes the existence of transmission lines. However, the technologies that will be necessary to install, mainly solar and wind, to supply the final national energy demand was simulated using the RE potential distributed throughout the Chilean territory. That will be totally possible, because according to Chile's Energy Ministry [47], the available solar and wind resource potential in Chile has been estimated at about 1,375 GW (where RE potentials from Patagonia are not considered), which means 16 times more than the total installed capacity we have found would be required, based on this study.

Renewable energies, along with electricity and heat storage technologies, will become key drivers to achieve the transition toward a fully sustainable energy system in Chile. The solar irradiation levels throughout the country will also play an important role, which can allow the PV prosumer contribution in the power and heat sectors, and for electrification of some roads and rail transportation modes as well. Moreover, in the country, areas where the copper industry is located and where the water stress will be higher, there is also enough solar potential to supply the energy demand for copper mining and water desalination [48,49,50]. In addition, the recommendations by Nasirov et al. [51] and Haas et al. [52] must also be considered in order to accelerate the deployment of RE in general, and the solar technologies in particular.

Also for sustainable fuels production, solar and wind technologies will be key. Sustainable RE-based fuels will be mainly required for marine and aviation transportation. In the case of hydrogen production, the Atacama Desert represents the best place in the world [53]. At the same time, although there are no existing transmission lines that connect Patagonia with the rest of Chile to directly use the electricity generated from wind potential, this zone has the best combination between solar PV and wind to produce synthetic fuels [53,54]. Both the Atacama Desert solar potential and the Chilean Patagonia solar PV and wind potentials will play an important role in producing sustainable fuels in the energy transition for Chile.

Moreover, a difference of our results with the reality in the interval between 2015-2020 can be seen in the power and heat sectors. The first simulations showed that the solar PV and wind onshore installed capacity to generate electricity could reach 2.3 GW and 7.4 GW by 2020, respectively. According to the CNE [6], solar PV technology is being installed more than the wind onshore PP, which in 2020 will reach 2.6 GW and 2.4 GW, respectively. This is a consequence of the cost-optimal approach of the model due to the low cost for electricity generation from wind in Patagonia, a disconnected area of the Chilean electric system.

However, it can be adjusted in future research as given constraints, in order to project the energy transition, related to the renewable technology projected in construction throughout the country. Additionally, it can also be estimated that in order to contemplate the transmission lines and what investment would be necessary to do that. The trade-off between storage (at the site of generation) and power transmission (linking separated sites of generation and demand) is being discussed in other parts of the world [55] and will be of the highest interest for future policymaking in Chile. Earlier research found that the electricity exchange of Chile with neighboring countries may not generate additional value [38]. It will be of high interest to learn how country-internal electricity transmission will generate additional value.

4.3. Future works recommendation

The understanding of how to transition toward a fully sustainable energy system for Chile is just getting started. As a next step, we propose to do an additional study, which subdivides the country into few nodes. This will enable us to identify each node's main consumption points in order to match the final energy demand at a more local level. Under this system, we also suggest carrying out a comparison of different scenarios such as an energy system with a full separation of regions and sectors, and another fully integrated one. Each of them should be compared with the current policy scenario, and the compatibility of the CO_2 budget as well. These and other scenarios can provide new insights to find the best energy transition pathway for Chile. It might also be extrapolated to other countries.

Our results suggest that there are no major technical and economic barriers to achieve a fully renewable-based energy system in Chile by 2050. However, social acceptance and appropriate energy policy targets could be potential barriers. Therefore, we suggest analyzing those aspects in more depth in order to identify the challenges to materialize the energy transition in this country.

Finally, for future studies, we recommend estimating the socio-economic benefits and environmental externalities during the transition toward a 100% RE energy system, such as job creation, which seems to be highly attractive [56], and the reduction of contaminating materials, beyond GHG.

5. Conclusions

The renewable energy potential in Chile is abundant, and RE and storage technologies can sufficiently supply energy at every hour throughout the year in Chile, for all sectors. Low-cost solar PV and wind electricity will be the main drivers to achieve a fully sustainable energy system. We conclude that an energy system based on 100% RE is technically feasible and economically viable across all energy sectors, mainly based on renewable electricity. Moreover, in 2050, this energy system would become about 50% more energy-efficient than the current one. This increase in system energy efficiency is a key reason for the reduction in total system cost from 114 €/MWh in 2015 to 85 €/MWh in 2050. Consequently, this energy transition would imply to zero the GHG emissions from all energy sectors supporting the 1.5ºC scenario of the Paris Agreement and achieve independence of fossil fuels by 2050.

Carrying out the energy transition towards a system based on 100% RE requires ambitious national policy targets, which go beyond a net-zero CO_2 balance of the country. We suggest that upcoming studies should consider modeling with higher spatial resolutions, from the energy demand point of view, in order to get accurate insights into the complex energy system with the goal of finding the best policy scenarios that will allow Chile to become one of the first countries around the world with a fully sustainable energy system.

Acknowledgments

This work was supported by the Vice-Rectorate of Research, Development & Arts of the Universidad Austral de Chile, the Erasmus+ Traineeships program through of the University of Jaén, and the Research Foundation of LUT University. The first author also thanks the Vice-Rectorate of Research of the University of Jaén for the “Acción 4” scholarship: “Ayudas predoctorales para la Formación de Personal Investigador”. The authors thank Ashish Gulagi for valuable proofreading and reviewers for their constructive and detailed comments for further improvement of the paper.

Appendix/Supplementary material

Supplementary material to this article can be found online at http://doi.org/10.5278/ijsepm.3385

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