The Role of Renewable Energy in the Transition Toward a Fully Sustainable Energy System in Chile Across Power, Heat, Transport and Desalination Sectors

Juan Carlos Osorio-Aravena[1,2], Arman Aghahosseini[3], Dmitrii Bogdanov[3], Upeksha Caldera[3], Emilio Muñoz-Cerón[2] and Christian Breyer[3]

[1] Universidad Austral de Chile, Coyhaique (Chile)

[2] University of Jaén, Jaén (Spain)

[3] LUT University, Lappeenranta (Finland)

Abstract

Renewable energies will play a significant role in a sustainable energy system in order to match the goal under the Paris Agreement. However, to achieve the goal it will be necessary to find the best country pathway, with global repercussion. This study reveals that an energy system based on 100% renewable resources in Chile could be technically feasible and even more cost-efficient than the current system. The Chilean energy system transition would imply a high level of electrification across all sectors, direct and indirectly. Simulation results using the LUT Energy System Transition model show that the primary electricity demand would rise from 31.1 TWh to 231 TWh by 2050, which represent about 78% of the total primary energy demand. Renewable electricity will mainly come from wind and solar energy technologies. Consequently, the levelized cost of energy will be reduced in 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 modelling

1. Introduction

Chile is a country highly dependent on fossil fuels. In 2015, the share of this kind of resources was 70% of the total primary energy supply (ME, 2017). The energy sector has been responsible for major greenhouse gas (GHG) emissions of the country, represented by about 77% of the total (ME, 2017). According to Climate Action Tracker (2018), Chile is a highly insufficient country, because the National Determined Contribution and planned energy policy are not in line with the goal under the Paris Agreement.

On the other hand, according to the Climatescope report by BNEF (2018), Chile has become the world leader of the emerging markets in the use and enabling of 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 potentials, in particularly solar and wind. Actually, nowadays it is highly competitive to produce electricity from these renewable sources in Chile, without subsidies (ME and GIZ, 2018). 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 transform rapidly its existing energy system, in a sustainable one independent of fossil fuels.

The deployment of RE technologies in Chile has advanced faster than planned. In the case of non-conventional renewable energy (NCRE), whose contribution in electricity generation reached 1.27 TWh, in December 2018, has exceeded 3 times the mandatory target for 20257 and 20698 Laws (CNE, 2019) – a progressive increase of the NCRE participation until reaching 20% by 2025. At the end of 2018, the NCRE reached 20.8% of the total installed capacity in the country, including hydropower plants larger than 20 MW, the percentage increases up to 47.0% (CNE, 2019). However, the total GHG emissions in the energy sector have not been reduced (MAM, 2018).

doi:10.18086/swc.2019.31.03 Available at http://proceedings.ises.org

Therefore, it is necessary to increase the current goal in order to meet the set international climate targets. Actually, although it has a long-term energy planning (ME, 2018), it is not contemplating an energy system based on 100% RE for all sectors. To our knowledge, no scientific articles exist which discuss a system based on 100% RE applied to this country for all its energy sectors. However, 100% renewable energy supply is an emerging topic of high interest in practically all parts of the Americas (Aghahosseini et al., 2019).

Get an energy system with high levels of sustainability, country by country coordinated with the global context, it is one of the major challenges in order to comply with the Paris Agreement. Hence, this study has the purpose of modelling a transition in Chile toward a fully sustainable energy system across all sectors, using the LUT University (LUT) Energy System Transition model (Bogdanov et al., 2019a; Ram et al., 2019a). 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 can be helpful for other nations of the region, and act as an example for other countries with similar conditions.

This paper is organized as follows: Section 2 describes the methods used, which was based on the LUT Energy System Transition model. The results of the model simulations on the role of renewable energy in attaining a fully sustainable energy system for Chile (including the power, heat, transport, and desalination sectors) in the transition period from 2015 to 2050, are presented in Section 3. Section 4 discusses the meaning of these results, some limitations and first insights from them, and a proposal and recommendation for improving the energy transition pathway for Chile are given as well. The paper ends with a conclusion and a suggestion for future studies in Section 5.

2. Methods

The LUT Energy System Transition model 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 objective of the model is to create an energy system based on 100% RE for the transition period from 2015 until 2050. The modelling tool presents the results of the energy system transition in five-year time steps, from 2015 to 2050. Fig. 1 shows the general process flow of the LUT Energy System Transition model. A detailed description of the model can be found in Bogdanov et al. (2019a) and Ram et al. (2019a). The specific sector coupling of the integrated power and heat sectors is describe in detail in Bogdanov et al. (2019b).

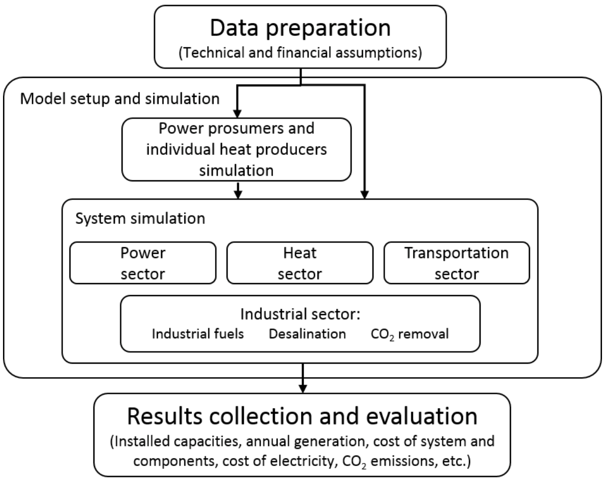

Fig. 1: Fundamental structure of the LUT Energy System Transition model (Bogdanov et al., 2019a; Ram et al., 2019a)

As a first step in data preparation, data collection of 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. (2019) 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 (IEA, 2016), long-term total final energy demand by energy forms and sectors was determined (see Fig. 2). 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. (2019) 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.

The desalination demand was projected based on water stress greater than 40% through a function of the water stress and total water demand for specific years during the transition period, according to Caldera et al. (2016; 2019). Then, it became into energy demand for water desalination. The total water demand includes the projected demand from the municipal, industrial and agricultural sectors.

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

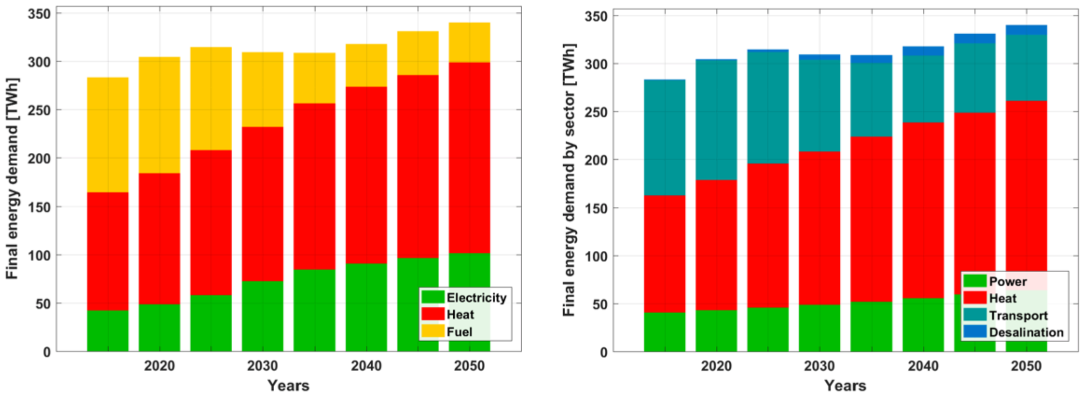

Fig. 2: Final energy demand by energy form (left) and by sector (right) through the transition

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 (Afanasyeva et al., 2018; Bogdanov and Breyer, 2016; Verzano, 2009). The potentials for biomass and waste resources were classified into biogas/solid residues and solid wastes, based on Bunzel et al. (2009). In addition, geothermal energy potential was estimated according to Gulagi et al. (2017).

Additionally, the financial and technical assumptions for all technologies involved in the model 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 run based on the model setup and simulation of LUT Energy System Transition model. In 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. In the second step, the simulation was carried out on a sectorial basis for this country from 2015 to 2050, in five-year time periods. The modelling tool is fully described by Bogdanov et al. (2019a) and Ram et al. (2019a).

The main objective of the simulation for the transition period was to create a fully sustainable energy system, as defined in Child et al. (2018), for Chile while simultaneously reducing the GHG emissions to zero and attaining energy independence. The simulation was also crucial for understanding the cost of this new energy system, based on 100% RE by 2050. All of this was done to define an energy scenario that achieves the defined climate target at the country level.

3. Results

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 GHG emissions to zero by 2050, while at the same time gaining energy independence.

Fig. 3 (top left) shows the results of the primary energy demand by sector through the transition from 2015 to 2050. In this bar-graph, we can appreciate that the share of primary energy demand by sector does not vary significantly during the transition. The desalination sector will be the exception due to the increasing water stress projected in the coming decades. Another result that we can see in Fig 3 (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 during the transition period (see Fig. 3, top right), even assuming a sustainable economic growth. This will be the outcome of the more efficient energy system based on renewable resources and technological changes. As Fig. 3 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 MWh/person.

The modelling results reveal an inevitable massive electrification through the energy transition period for Chile. Primary renewable electricity would have a sustained growth from 31.1 TWh by 2015 to 231 TWh by 2050, (see Fig. 3, 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 Fig. 3 (bottom right), those high levels of direct and indirect electrification, which would come from renewable energy technologies, would become a much more energy efficient system if we compare it with an energy system based on current practices. An energy transition scenario with high renewable electricity level could be about 90% more efficient than another with low electrification levels.

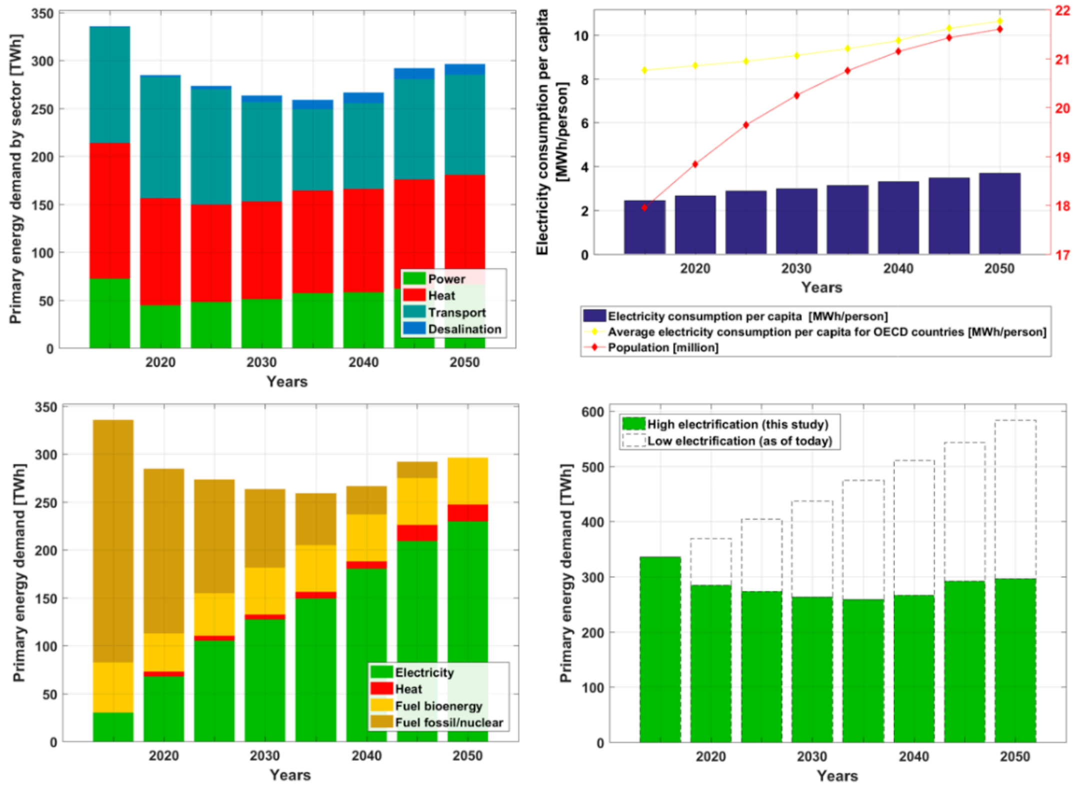

Fig. 3: Primary energy demand sector-wise (top left), electricity consumption per capita with population (top right), primary energy demand by energy form (bottom left), and efficiency gain in primary energy demand (bottom right) during the energy transition from 2015 to 2050

Fig. 4 shows the results of the installed capacity to generate electricity and heat by technology for power, heat, and transport sectors during the transition period. As can be seen in Fig. 4, solar and wind technologies would be predominant through the transition. In 2050, the total renewable installed capacity to generate electricity across all sectors would rise to about 85 GW; 55% for power and heat, 39% for transport, and 6% for desalination (see Fig. 4 top left, bottom left, and bottom right, respectively). From Fig. 4 (top right), we can see that solid biomass technologies will also be necessary to supply heat demand in the heat sector through the whole transition period.

The photovoltaic (PV) prosumers installed capacity could be up to one-third of the total capacity to generate electricity for power and heat energy demand by 2050. 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 Fig. 4 top left). Electrical and thermal energy storage technologies will also be needed to support the supply of the final electricity and heat demand. Diurnal battery storage will be important as it supports the PV and wind generation systems. Batteries for prosumers will start to emerge in 2025. Both battery storage for PP and adiabatic compressed air energy storage (A-CAES) would start to appear in the interval between 2030-2035. Additionally, electric heat pumps and other heating technologies will play an important role in supplying the heat demand through the energy transition across Chile. All of these results for power and heat sectors are presented in the Supplementary Material (Table S11).

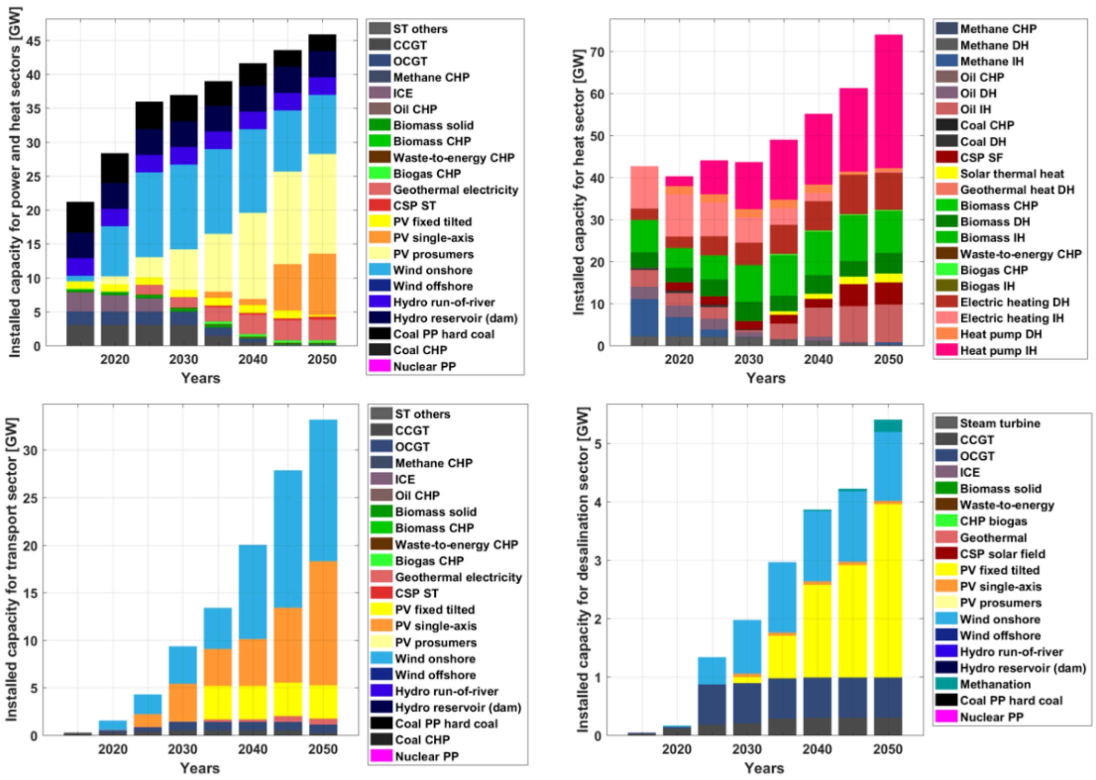

Fig. 4: Installed capacity by power technology for power and heat sectors (top left), installed capacity by heat technology (top right), installed capacity by power technology for transport sector (bottom right), and installed capacity by power technology for desalination, through the transition period

In the case of the transport sector, from 2025 to 2050, the renewable installed capacity to produce sustainable fuels (hydrogen, liquid, and renewable gas) would start to increase at an average annual growth rate of 9.3% (See Fig. 4 bottom left). Here, it also includes the installed capacity for CO_2 direct air capture technologies (Fasihi et al., 2019), which are used to produce some of the sustainable fuels. 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 complemented with low-cost electricity.

Desalination energy demand will be covered majorly by renewable electricity. Desalination demand will increase during the transition period due to the rising of water stress that is expected globally. To supply it in Chile, the results show that the country would be required to increase their renewable installed capacity from 0.03 GW in 2020 to 5.19 GW by 2050 (see Fig. 4 bottom right). Here, the solar and wind technologies would reach 58% and 23% of that installed capacity.

Of the almost 300 TWh of primary energy demand in the year 2050, about 78% would be supplied by renewable electricity technologies. As it is shown in Fig. 5 (top left and bottom left and right), the major contribution of electricity generation across all sectors in 2050 will come from wind onshore (50%), followed by solar PV (39%), and the remaining 11% by mainly hydropower with minor contributions of CSP, biomass, and geothermal PP. The solar PV prosumers would contribute with 24% of the electricity generation for power and heat sectors by 2050 (see Fig. 5 top left).

Fig. 5 (top right) shows heat generation from 2015 to 2050. The heat pumps' individual heating (IH) and district heating (DH) will be the key to covering the heat demand during the transition period, which can be supplied by renewable electricity. Heat pump IH will play a significant role through the transition, having a sustainable growth rising share of about 50% of heat generation by 2050. The remaining heat generation will come from biomass-based technologies (24%), and electric heating (15%), with nearly 9% from solar thermal, and a small part of synthetic gas produced from renewable energy that will replace fossil gas. Nevertheless, the storage of thermal technologies will also be necessary for the energy transition. The details of these results about electricity and heat generation for power and heat sectors, including electric and heat storage technologies, are presented in the Supplementary Material (Tables S14-S17).

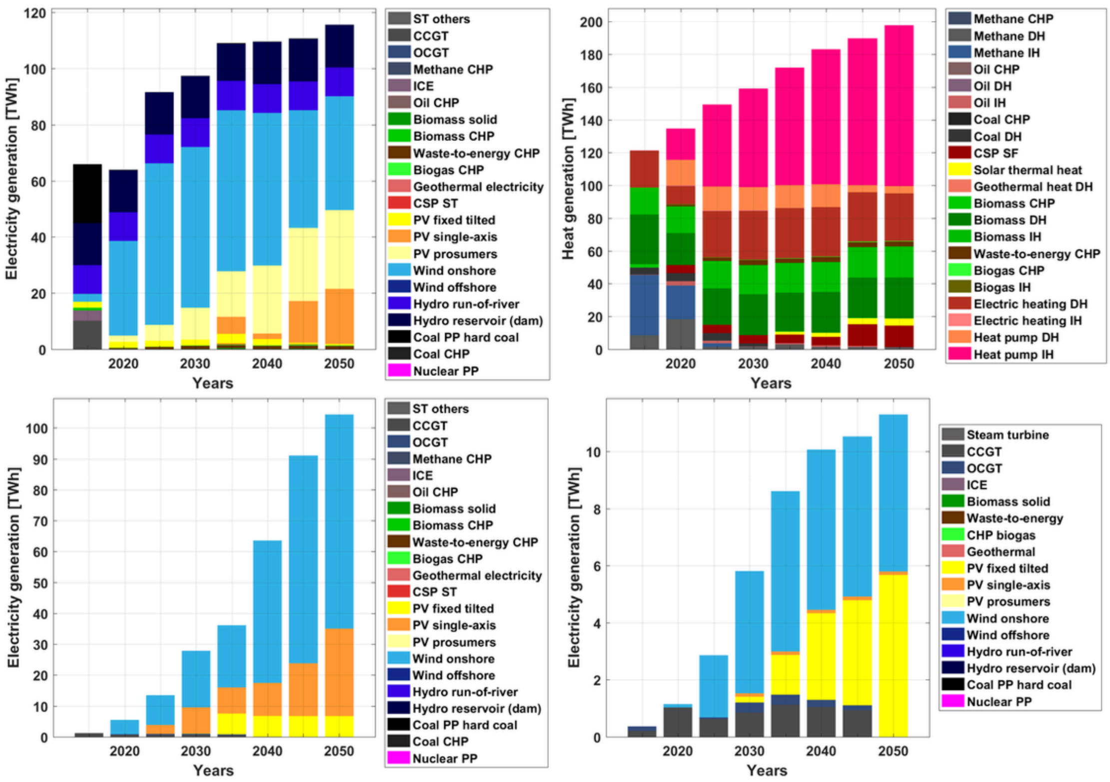

Fig. 5: Electricity generation by power technology for power and heat sectors (top left), heat generation by heat technology (top right), electricity generation by power technology for transport sector (bottom left), and electricity generation by power technology for desalination sector (bottom right) during the energy transition period

In the transport sector, as is indicated in Fig. 5 (bottom left), renewable electricity generation will predominate from 2020. In 2050, nearly 66% of electricity generation would come from wind onshore complemented for PV single-axis tracking (27%) and PV fixed tilted (7%). The final energy demand for transportation by 2050 would be covered by electricity directly (40%), followed by 34% of synthetic fuels (liquid and gas) and 26% of hydrogen. The production of sustainable fuels for transportation demand could be fully supply based on renewable electricity from 2040 onwards. The results to cover the energy demand for transportation by mode, segment, and sustainable fuels production can be seen in the Supplementary Material (Tables S18-S21).

Energy demand for water desalination can be fully supplied from renewable electricity by 2050. In that year, wind and solar PV technologies could contribute 49% and 51% of the electricity generation, respectively (see Fig. 5 bottom right). Storage technologies will also be needed for the desalination sector, since using batteries for raising the full load hours of the desalination plants is the lower cost option than investing in more desalination capacities and buffering the clean water in water storage (Caldera and Breyer, 2018). The installed capacity of which would occur mainly from 2035 and, in 2050, the batteries output will cover 28% of 10.2 TWh demanded desalination (for more details of these results, see Tables S22-S23 in the Supplementary Material).

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 Fig. 6, left). As can be seen in Fig. 6 (right), the levelized cost of energy (LCOE) 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 LCOE 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 results by sector through the transition period are available in the Supplementary Material (Tables S24-S27).

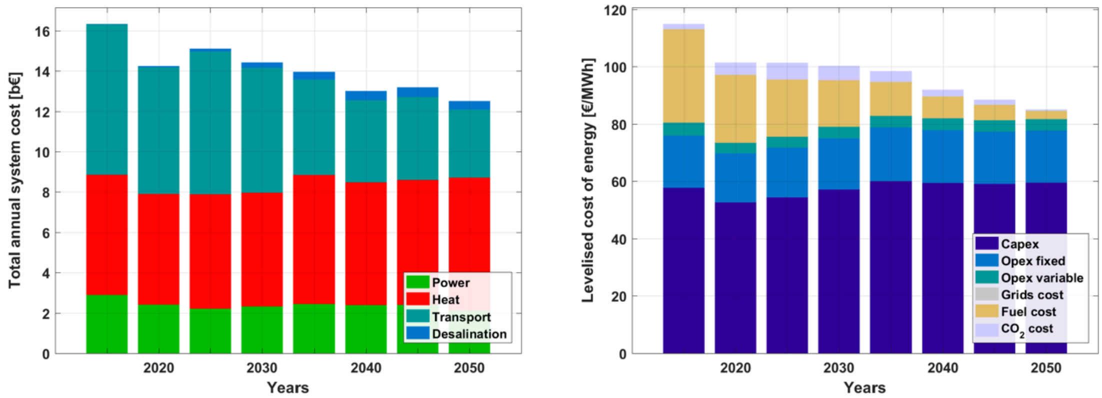

Fig. 6: Annual system costs, sector-wise (left) and levelized cost of energy (right) through the transition

One of the most important consequences of our results is associated with energy-related GHG emissions. An energy system based on 100% RE by 2050 will imply a full defossilization by 2050. As is indicated in Fig. 7 (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 Fig. 7 (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 Fig. 7 (right). All of this will mainly be possible thanks to high levels of renewable electricity supply across the power, heat, transport, and desalination sectors.

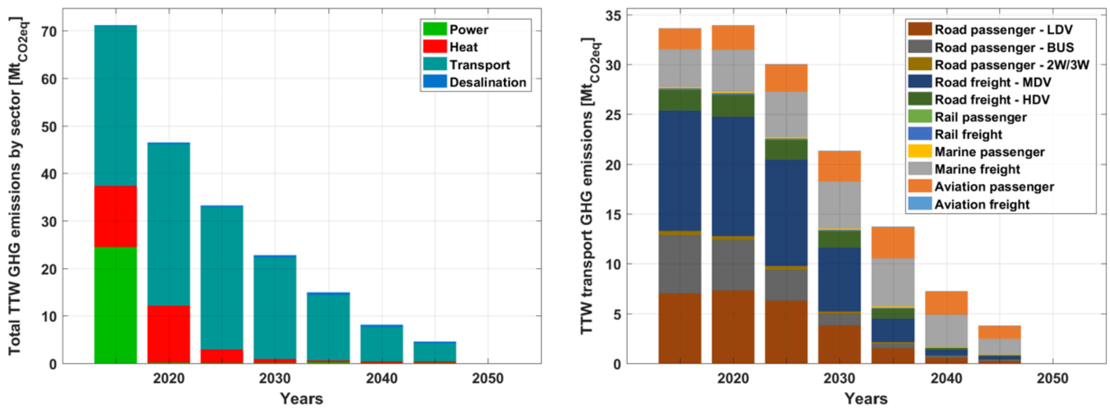

Fig. 7: Sector-wise GHG emissions (left) and GHG emissions in the transport sector by mode and segment (right), during energy transition from 2015 to 2050

4. Discussion

This study illustrates that to achieve a Chilean energy system based on 100% RE by 2050 is possible. These energy transition results for Chile, across the sectors of power, heat, transport and desalination, are the first ones of this kind. Previous studies to attain a fully renewable energy system (Haas et al., 2018; Haas et al., 2019) and at least 60% of the electricity generated from RE sources (Maximov et al., 2019; Muñoz et al., 2017; Raugei et al., 2018) have been conducted to cover most of the demand from the power sector. According to Chile's government, in his Long-term Energy Planning report (ME, 2018), 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 of this country, based on a fully sustainable energy system sector-wise, 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 influence Chile to focus on a more decentralized and independent country, in energy terms. Highly renewable energy supply is discussed for practically all regions in the world (Hansen et al., 2019), and 100% renewable energy supply is technically feasible and economically viable as pointed out by Brown et al. (2018).

The main sources of energy for the energy supply in Chile are solar and wind energy, not surprising, since the best solar sites and the best wind sites in the world are in Atacama Desert and Patagonia, respectively. The contribution to the electricity generation across all sectors is 50% (wind), 39% (solar PV) and 11% (others). These findings are roughly in line with the earlier findings for Chile in an integrated study for South and Central America (Barbosa et al., 2017).

One of the main limitations of these preliminary results for Chile is that the total final energy demand of the country was considered as one consumption 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, especially because according to ME (2014), the solar and wind renewable energy available potential in Chile has been estimated at about 1,375 GW, which means 16 times more than the total installed capacity we have found would be required, based on this study.

Renewable energy, along with electricity and heat storage technologies, will become key drivers to achieve the transition toward a fully sustainable energy system in Chile. It will be primarily thanks to solar conditions in the north and wind potential in the south. The solar irradiation levels throughout the country will also play an important role, which can allow the prosumer contribution in the power and heat sectors, and for electrification of some roads and rail transportation modes as well. Additionally, in country areas where the water stress will be higher, there is also enough solar potential to supply the energy demand for desalination and pumping the water to the sites of demand.

For the sustainable fuels production, solar and wind technologies will be key. Sustainable RE-based fuels will be mainly required for marine and aviation transportation modes. In the case of hydrogen production, the Atacama Desert represents the best place of the world (Fasihi et al., 2016). At the same time, although there are not existing transmission lines that connect Patagonia with the rest of Chile to use directly the electricity generated from wind potential, this zone has the best combination between solar PV and wind to produce synthetic fuels (Fasihi et al., 2016; Fasihi et al., 2017). 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 can reach 2.3 GW and 7.4 GW by 2020, respectively. According to the CNE (2019), solar PV technology is being more installed than wind onshore PP, which in 2020 will reach 2.6 GW and 2.4 GW, respectively. That 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 with 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 site of generation) and power transmission (linking separated sites of generation and demand) will be of highest interest for future policy making in Chile. Earlier research found that the electricity exchange of Chile with neighbouring countries may not generate additional value (Barbosa et al., 2017). It will be of high interest to learn how country-internal electricity transmission will generate additional value.

In any case, 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 a 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 fully separate regional-sectorial, or an energy system that fully integrates regional-sectorial. Each of them should be compared with the current policy scenario. These and other scenarios can provide new insights to find the best energy transition pathway for Chile. It can also be extrapolated to other countries. 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 (Ram et al., 2019b) 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 driver 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. Consequently, this energy transition would imply a reduction of the GHG emissions to zero, and independence of fossil fuels by 2050 in this country.

Carrying out the energy transition towards a system based on 100% RE requires ambitious national policies targets, which go beyond a net zero CO_2 balance of the country. We suggest that upcoming studies should consider modelling 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”.

References

Afanasyeva, S., Bogdanov, D., Breyer, Ch., 2018. Relevance of PV with single-axis tracking for energy scenarios. Sol. Energy 173, 173-191. https://doi.org/10.1016/j.solener.2018.07.029

Aghahosseini, A., Bogdanov, D., Barbosa, L.S.N.S., Breyer, Ch., 2019. Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030. Renew Sustain Energy Rev 105, 187-205. https://doi.org/10.1016/j.rser.2019.01.046

Barbosa, L.S.N.S., Bogdanov, D., Vainikka, P., Breyer, Ch., 2017. Hydro, wind and solar power as a base for a 100% Renewable Energy supply for South and Central America. PLoS ONE 12, e0173820. https://doi.org/10.1371/journal.pone.0173820

Bloomberg New Eenergy Finance (BNEF), 2018. Emerging Markets Outlook 2018. Available at: http://global-climatescope.org/. [accessed: 05/02/2019]

Bogdanov, D., Breyer, Ch., 2016. North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manag. 112, 176-190. https://doi.org/10.1016/j.enconman.2016.01.019

Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Oyewo, S., Barbosa, L.S.N.S., Breyer, Ch., 2019a. Radical transformation pathway towards sustainable electricity via evolutionary steps, Nature Communications 10, 1077. https://doi.org/10.1038/s41467-019-08855-1

Bogdanov, D., Toktarova, A., Breyer, Ch., 2019b. Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: case for Kazakhstan. Appl. Energy, in press

Breyer, Ch., Khalili, S., Bogdanov, D., 2019. Solar photovoltaic capacity demand for a sustainable transport sector to fulfil the Paris Agreement by 2050. Prog Photovolt Res Appl. 1-12. https://doi.org/10.1002/pip.3114

Brown, T.W., Bischof-Niemz, T., Blok, K., Breyer, Ch., Lund, H., Mathiesen, B.V., 2018. Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. Renew Sustain Energy Rev 92, 834-847. https://doi.org/10.1016/j.rser.2018.04.113

Bunzel, K., Zeller, V., Buchhorn, M., Griem, F., Thrän, D., 2009. Regionale Und Globale Räumliche Verteilung von Biomassepotenzialen. Leipzig. Available at: https://literatur.thuenen.de/digbib_extern/dn047233.pdf

Caldera, U., Bogdanov, D., Breyer, Ch., 2016. Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate. Desalination 385, 207-216. http://dx.doi.org/10.1016/j.desal.2016.02.004

Caldera, U., Breyer, Ch., 2018. The role that battery and water storage play in Saudi Arabia's transition to an integrated 100% renewable energy power system, Journal on Energy Storage 17, 299-310. https://doi.org/10.1016/j.est.2018.03.009

Caldera, U., Breyer, Ch., 2019. Assessing the potential for renewable energy powered desalination for the global irrigation sector. Science of the Total Environment, in pressChild, M., Koskinen, O., Linnanen, L., Breyer, Ch., 2018. Sustainability Guardrails for Energy Scenarios of the Global Energy Transition. Renew Sustain Energy Rev 91, 321-334. https://doi.org/10.1016/j.rser.2018.03.079

Climate Action Tracker, 2018. Available at: https://climateactiontracker.org/countries/chile/. [accessed: 05/02/2019]

Comisión Nacional de Energía (CNE), 2019. Reporte mensual ERNC. Volumen N° 29. Available at: https://www.cne.cl/wp-content/uploads/2015/06/RMensual_ERNC_v201901.pdf. [accessed: 01/02/2019]

Fasihi, M., Bogdanov, D., Breyer, C., 2016. Techno-economic assessment of Power-to-liquids (PtL) fuels production and global trading based on hybrid PV-wind power plants. Energy Procedia 99, 243-268. doi:10.1016/j.egypro.2016.10.115

Fasihi, M., Breyer, Ch., 2017. Synthetic Methanol and Dimethyl Ether Production based on Hybrid PV-Wind Power Plants. In: 11th International Renewable Energy Storage Conference (IRES 2017). http://bit.ly/2qvsLYf.

Fasihi, M., Efimova, O., Breyer, Ch., 2019. Techno-economic assessment of CO2 direct air capture plants, Journal of Cleaner Production 224, 957-980. https://doi.org/10.1016/j.jclepro.2019.03.086

Gulagi, A., Choudhary, P., Bogdanov, D., Breyer, Ch., 2017. Electricity system based on 100% renewable energy for India and SAARC. PLoS One 12, 1-27. https://doi.org/10.1371/journal. pone.0180611

Haas, J., Cebulla, F., Nowak, W., Rahmann, C., Palma-Behnke, R., 2018. A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply. Energy Convers. Manag. 178, 355–368. https://doi.org/10.1016/j.enconman.2018.09.087

Haas, J., Nowak, W., Palma-Behnke, R., 2019. Multi-objective planning of energy storage technologies for a fully renewable system: Implications for the main stakeholders in Chile. Energy Policy 126, 494-506. https://doi.org/10.1016/j.enpol.2018.11.034

Hansen, K., Breyer, Ch., Lund, H., 2019. Status and Perspectives on 100% Renewable Energy Systems. Energy 175, 471-480. https://doi.org/10.1016/j.energy.2019.03.092

International Energy Agency (IEA), 2016. Available at: https://www.iea.org/sankey/#?c=Chile&s=Balance. [accessed: 16/01/2019]

Maximov, S., Harrison, G., Friedrich, D., 2019. Long term impact of grid level energy storage on renewable energy penetration and emissions in the Chilean electric system. Energies 12(6), 1070. https://doi.org/10.3390/en12061070

Ministerio de Energía del Gobierno de Chile (ME), 2014. Energías Renovables en Chile: El potencial eólico, solar e hidroeléctrico de Arica a Chiloé. Available at: http://www.minenergia.cl/archivos_bajar/Estudios/Potencial_ER_en_Chile_AC.pdf. [accessed: 11/07/2019]

Ministerio de Energía del Gobierno de Chile (ME), 2017. Plan de Mitigación de Gases de Efecto Invernadero para el Sector Energético. Available at: http://www.energia.gob.cl/sites/default/files/plan_de_mitigacion_sector_energia.pdf. [accessed: 05/02/2019]

Ministerio de Energía del Gobierno de Chile (ME), 2018. Proceso de Planificación Energética de Largo Plazo. Available at: http://pelp.minenergia.cl/informacion-del-proceso/resultados. [accessed: 11/07/2019]

Ministerio de Energía del Gobierno de Chile and Deutsche Gesellschaft für Internationale Zusammenarbeit (ME and GIZ), 2018. https://www.4echile.cl/4echile/wp-content/uploads/2019/01/Libro_ERNC_Chile_eng.pdf. Available at: [accessed: 11/07/2019]

Ministerio de Medio Ambiente del Gobierno de Chile (MMA), 2018. Tercer informe bienal de actualización de Chile sobre el cambio climático. Available at: https://mma.gob.cl/wp-content/uploads/2018/12/3rd-BUR-Chile-SPanish.pdf. [accessed: 11/07/2019]

Muñoz, F., Pumarino, B., Salas, I., 2017. Aiming low and achieving it: A long-term analysis of a renewable policy in Chile. Energy Econ. 65, 304-314. http://dx.doi.org/10.1016/j.eneco.2017.05.013

Ram, M., Bogdanov, D., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa L.S.N.S., Fasihi, M., Khalili, S., Dahlheimer, B., Gruber, G., Traber, T., De Caluwe, F., Fell, H.-J., Breyer, Ch., 2019a. Global Energy System based on 100% Renewable Energy – Power, Heat, Transport and Desalination Sectors. Study by LUT University and Energy Watch Group, Lappeenranta, Berlin. Available at: http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf. [accessed: 09/05/2019]

Ram, M., Aghahosseini, A., Breyer, Ch., 2019b. Job creation during the global energy transition towards 100% renewable power system by 2050. Technological Forecasting and Societal Change. https://doi.org/10.1016/j.techfore.2019.06.008

Raugei, M., Leccisi, E., Fthenakis, V., Escobar, R., Simsek, Y., 2018. Net energy analysis and life cycle energy assessment of electricity supply in Chile: Present status and future scenarios. Energy 162, 659-668. https://doi.org/10.1016/j.energy.2018.08.051

Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D., Breyer, Ch., 2019. Long term load projection in high resolution for all countries globally. Int. J. Electr. Power Energy Syst. 111, 160-181. https://doi.org/10.1016/j.ijepes.2019.03.055

Verzano, K., 2009. Climate Change Impacts on Flood Related Hydrological Processes: Further Development and Application of a Global Scale Hydrological Model. doi:10.17617/2.993926

Appendix A. Supplementary Material

Supplementary Materials can be found in the following link:
https://www.researchgate.net/publication/334707589_The_Role_of_Renewable_Energy_in_the_Transition_Toward_a_Fully_Sustainable_Energy_System_in_Chile_Across_Power_Heat_Transport_and_Desalination_Sectors

Appendix B. Abbreviations

A-CAES	Adiabatic compressed air energy storage
CAPEX	Capital expenditures
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
CNE	Comisión Nacional de Energía (National Energy Commission)

CO_2	Carbon dioxide
CSP	Concentrated solar thermal power
DH	District heating
GHG	Greenhouse gas
GW	Gigawatt
HDV	Heavy duty vehicle
ICE	Internal combustion engine
IEA	International Energy Agency
IH	Individual heating
LCOE	Levelized Cost of Energy
LDV	Light duty vehicle
LUT	Lappeenranta University of Technology
MDV	Medium duty vehicle
ME	Ministerio de Energía del Gobierno de Chile (Chile's Ministry of Energy)
MMA	Ministerio de Medio Ambiente del Gobierno de Chile (Chile's Ministry of Environment)
MW	Megawatt
MWh	Megawatt hour
NCRE	Non-Conventional Renewable Energy
OCGT	Open cycle gas turbine
OECD	Organization for Economic Co-operation and Development
OPEX	Operational expenditures
PP	Power plant
PV	Photovoltaic
RE	Renewable Energy
SM	Supplementary Material
ST	Steam turbine
TTW	Tank-to-wheel
TWh	Terawatt hour
2W	two wheelers
3W	three wheelers
€	Euro