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Evaluation of the Levelized Cost of Energy with New Costs for Concentrating Solar Power Tower Plants in Northern Chile and Impact of Green Taxes

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Abstract. The world is undergoing an energy transformation, from a system based on fossil fuels to a system based on renewable energy, in order to reach the Paris Agreement target. Chile is no exception, and through the Asociación de Concentración Solar de Potencia (ACSP) has generated a new cost structure for tower-based Concentrated Solar Power (CSP) technology in the framework of the Long-Term Energy Plan, which updates the costs reported in previous studies. The changes experienced in this cost structure make it necessary to study the impact of this cost structure on the levelized cost of energy (LCOE). This work develops simulations of CSP tower plants analyzing their generation and the LCOE based on the new cost structure mentioned, for the north of Chile between the Arica and Parinacota region and the Coquimbo region. The most relevant results show a significant reduction in the LCOE, compared to studies from 2020, reaching a minimum LCOE value of 52,6 USD/MWh. On the other hand, the impact on the net social benefit of including the green tax to the merit order of each of the generating plants that make up the electric park until 2021 is studied, which yields a negative impact under current legislation.

Keywords: LCOE, CSP, Solar Tower, Chilean Electrical Market

1. Introduction

Chile is recognized worldwide for having privileged conditions for the availability of renewable resources. In terms of solar energy for electricity generation, northern Chile has a very low atmospheric attenuation compared to other locations in the world [1], in conjunction with the highest annual average direct solar radiation in the world. Especially in the Atacama Desert high direct solar radiation and clear skies exist most of the year [2]. Given the above and that the prices of electricity production by CSP technology in the last bidding round for regulated customers in Chile went below 34 USD/MWh it makes sense to study where this type of technology could be located and what levelized cost of energy (LCOE) could be achieved in those locations.

2. Methodology

The Association for Concentrating Solar Power (ACSP) has published a report on CSP technology costs updated to the year 2021 so that these costs can be considered in long-term strategic planning of the country [3]. Three configurations are studied depending on the target demand to be supplied:

- CSP for Peak demand, SM=1,7 and TES=6,0 hrs.

- CSP for Peak demand and part of the night, SM = 2,0 and TES=9,0 hrs.
- CSP for Peak and all-night demand, SM=2,5 and TES=13,0 hrs.

For these configurations a tower plant with molten salts (sodium nitrate) as heat transfer fluid with a gross capacity of 111.2 MWe, turbogenerator efficiency of 42,5% and a heliostat of 144.4 m2 area are chosen.

Simulations are performed using the System Advisor Model (SAM) [4] software for different locations in Chile. The sites chosen are those which were submitted by Fraunhofer Chile Research to the Ministry of Energy with cloudiness index less than 5%. Thus, 63 sites have been qualified in the north of Chile, ranging from the Region of Arica and Parinacota to the Region of Coquimbo.

2.1. Cost Structure

Table 1 shows the cost structure for the different configurations analyzed. It was assumed that the operating cost structure considers a variable cost of 3,5 USD/MWh and a fixed capacity cost of 66 USD/kW per year. Additionally, according to soiling estimates for the Atacama Desert [5] it has been considered that it is necessary to clean the heliostat field 35 times every year, so that the reflectivity of the field does not drop below 0,90. This has an impact on water consumption associated with field cleaning. For this purpose, it has been considered that water has a price of 5,0 USD/m^3 and that consumption is 07 l/m^2, of aperture area. Additionally, the water consumption associated with the power cycle was considered, which is calculated for each of the locations according to the result of each simulation by SAM at the same price indicated above. Finally, the parameters that are not mentioned in the table have the default number of the SAM Software itself.

Table 1. Direct cost structure for the tower CSP plant [3].

Item	Value	Units
Site improvement cost	0,5	\$/m^2
Heliostat field cost	120	\$/m^2
Tower cost fixed	2 250 000	USD
Receiver Reference cost	72 100 000	USD
Thermal energy storage cost	20	USD/kWh$_t$
Balance of plant cost	200	USD/kW$_e$
Power cycle cost	700	USD/kW$_e$

2.2. LCOE Calculation

The levelized cost of energy (LCOE) represents the cost of generating a unit of electrical energy. This parameter is widely used to compare different technologies in terms of economic viability. Equation 1 shows the mathematical formula to calculate the LCOE as reported by Hernandez-Moro and Martinez-Duart [6]. The discount rate (t) is assumed to be 5 [7] and 7% [8] depending on the case, and lifetime (i) of the CSP tower is 30 years [8] [9].

$$LCOE = \frac{\sum_{i=0}^{N} \frac{CAPEX_i}{(1+t)^i} + \sum_{i=0}^{N} \frac{OPEX_i}{(1+t)^i}}{\sum_{i=0}^{N} \frac{Production_i}{(1+t)^i}} \tag{1}$$

3. Results

The main results obtained in this work are summarized below. The LCOE results obtained for the different configurations and different discount rates are shown in Figure 1 and 2; in blue the configuration for peak demand is shown (SM 1,7 with 6,0 hours of storage), in yellow the configuration for peak demand and all night (SM 2,0 with 9,0 hours of storage) is shown, and in orange the configuration for the CSP plant for peak and overnight demand (SM 2,5 and 13,0 hours of TES) is shown.

Figure 1 shows the values for a discount rate of 7%. The SM 2,5 configuration and 13,0-hour storage (red color), presents a minimum of 60,0 USD/MWh, a maximum of 91,7 USD/MWh, an average of 66,7 USD/MWh and a mode in the lower class of LCOE, that is between 60 and 62,5 USD/MWh. On the other hand, the CSP configuration with SM 2,0 and TES=9,0 hrs (yellow color) gives a minimum LCOE of 65,0 USD/MWh, a maximum of 99,6 USD/MWh and an average of 72,4 USD/MWh. Finally, the CSP configuration for peak demand (SM 1,7 and TES=6,0 hrs, blue color) at a rate of 7% presents a minimum of 69,0 USD/MWh, a maximum of 105,8 USD/MWh and an average of 77,0 USD/MWh.

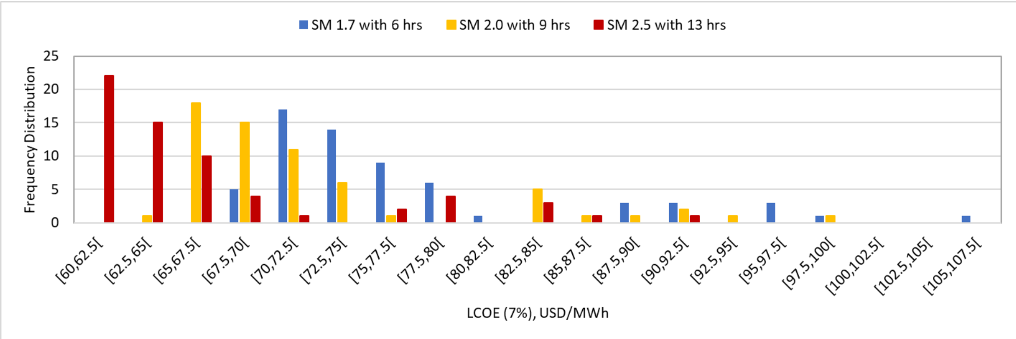

Figure 1. Histogram of LCOE values for different CSP plant configurations evaluated at a discount rate of 7%.

When evaluating the three configurations of the CSP plant at a discount rate of 5%, it is obtained that for the configuration with SM of 2,5, the minimum LCOE reaches 52,6 USD/MWh, with an average of 58,3 USD/MWh and a maximum of 80,1 USD/MWh, and its mode is in the class of 52,5 and 55 USD/MWh. On the other hand, the CSP configuration for peak demand and part of the night (SM 2,0 and TES=9,0 hrs, yellow color) evaluated at a rate of 5% obtains a minimum LCOE of 57,1 USD/MWh, an average LCOE of 63,5 USD/MWh and a maximum LCOE of USD 87,2 USD/MWh. Finally, the CSP configuration for peak demand (SM 1,7 and TES=6,0 hrs, blue color) at a rate of 5% presents a minimum of 60,8 USD/MWh, an average of 67,8 USD/MWh and a maximum LCOE of 92,9 USD /MWh. In all cases the LCOE is reduced by approximately 12% with respect to the 7% rate.

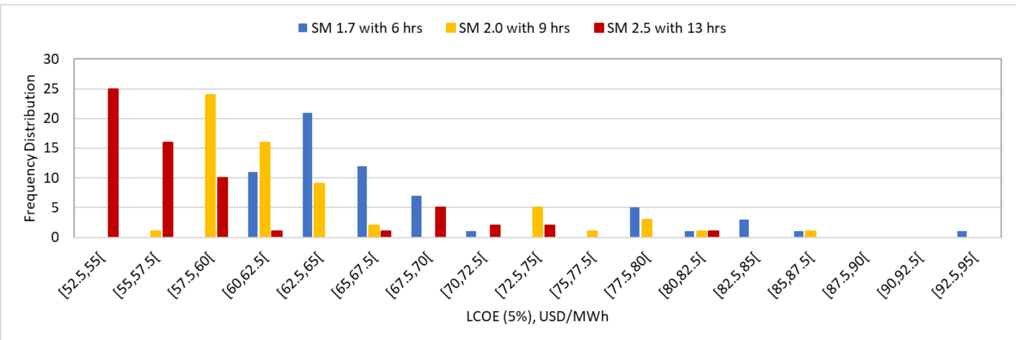

Figure 2. Histogram of LCOE values for CSP plant configurations evaluated at a discount rate of 5%.

In both figures it is possible to observe a downward trend for configurations with many hours of storage with a higher solar multiple and a lower discount rate. The results geographically for the 63 locations evaluated are shown in figure 3 and figure 4. This figure shows that as the solar multiple increases along with the hours of storage of the CSP plant the LCOE decreases so the color intensity of the points becomes stronger. Also, the locations within the Arica and Parinacota Region and the Antofagasta Region present lower LCOE compared to the Coquimbo Region.

Finally, a comparison was developed between the results obtained in this study with respect to the results of the work [5]. The comparison shows a reduction in the LCOE, reaching values around 16% below the values previously reported. This difference represents a significant reduction in energy cost compared to the minimum LCOE reported in [5], near Copiapó using the same cost structure (without transmission costs).

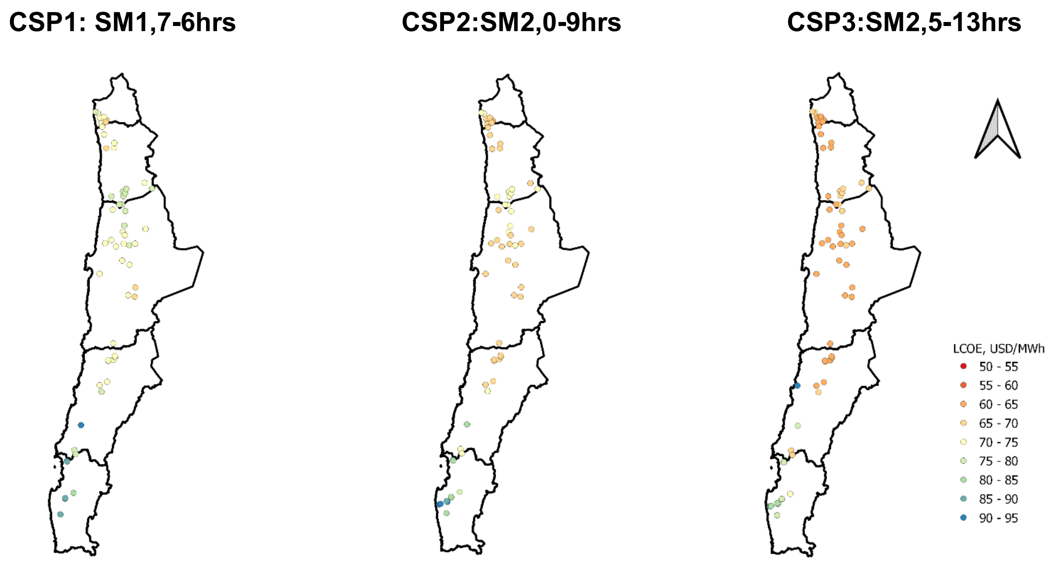

Figure 3. Geographically located LCOE results for the different configurations evaluated at a discount rate of 7%.

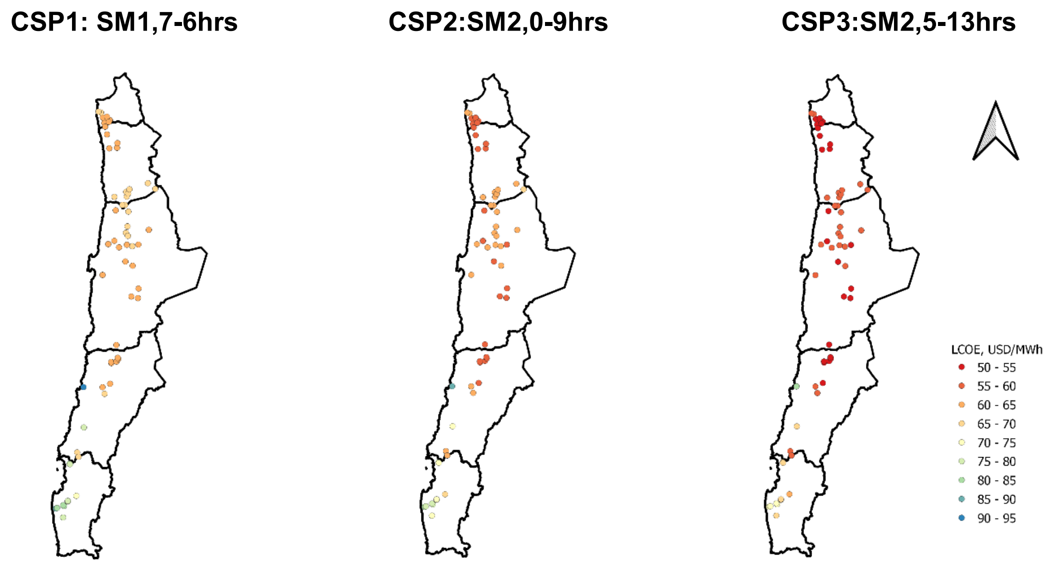

Figure 4. Geographically located LCOE results for the different configurations evaluated at a discount rate of 5%.

4. Evaluation Tax CO_2

As of July 2022, Chile's generating park is made up of 29 332 MW, where 57% of the installed capacity comes from renewable sources, while 43% is from traditional thermal sources, as indicated in Table 2.

Table 2. Chilean electricity market structure. [10][11].

Technology	Installed capacity MW (%)	Annual Generation 2021 GWh (%)
Wind	3 715 (12,66%)	7 095 (8,89%)
Hydro	7 260 (24,75%)	16 016 (20,06%)
Biomass	439 (1,50%)	1 946 (2,44%)
Geothermal	40 (0,14%)	317 (0,40%)
Solar CSP	108 (0,37%)	154 (0,19%)
Solar PV	5 145 (17,54%)	10 061 (12,60%)
Coal	4 641 (15,82%)	27 617 (34,58%)
Diesel Oil	4 180 (14,25%)	2 183 (2,73%)
Natural Gas	3 805 (12,97%)	14 464 (18,11%)
TOTAL	**29 332**	**79 853**

In Chile, carbon price instruments correspond to an environmental policy which emerges as a response to minimize environmental degradation at a lower social cost. These instruments respond to the damage generated, either by reducing emissions, offsetting them, or paying the price for the social cost. There are two types of instruments: carbon taxes and tradable emission permits. Carbon taxes can be a direct regulation on emissions, or indirect through the regulation of fossil fuels regulating the price through a charge on carbon content using emission factors. In both cases they oblige the generator to internalize the cost of the issues, but no limits are established. The emphasis is on price due to the social cost of polluting. In general terms, the rate of the tax should be equal to the marginal social damage of producing an additional unit of CO_{2eq}.

In the case of Chile, in September 2014, Law 20 780 [12] was approved, establishing three environmental taxes or green taxes, see Table 3.

Table 3. Taxes established by Law 20 780 [12].

Source type	Category	Contaminant
Mobile	First sell of vehicle	NO_x
Fixed	Global contaminants	CO_2
Fixed	Local contaminants	SO_2, NO_X, MP

Taxes on emissions from fixed sources have been in effect since January 1, 2017, regarding the emission report and the first payment of recorded emissions was in 2018 and taxes emissions from establishments with boilers and/or turbines with power equal to or greater than 50 MWt. Today, Chile has a CO_2 tax of 5 USD/tCO_2. The value was determined based on the social price of carbon estimated by the Ministry of Social Development. In 2017, the ministry adjusted its methodology for calculating the social cost of carbon and currently places it at around 32 USD.

The current government program proposes to gradually increase the CO_2 tax to 40 USD/tCO_2 and expand its scope with different emission sources.

The green tax adopted in Chile is a downstream tax, that means it does not tax the carbon content of the fuels used in the production processes, so the objective is distorted [13]. The determination of subparagraph 17 of article 8 of Law 20 780 excludes the tax from the calculation of the variable cost of each generating unit, which establishes a problem since from the environmental perspective it limits the theoretical compliance of the green tax for three main reasons (i) It does not establish a corrected value of the tax due to modifications by the social tax (ii) It does not alter the merit order dispatch (iii) It requires a mechanism for calculating and paying compensation for those generating units whose total unit cost (being the variable cost considered in dispatch plus the unit value of the tax) is greater than or equal to the marginal cost, which establishes the payment of compensation even to renewables generators, who do not emit pollutants subject to the tax . In other words, if the generating unit that determines the marginal cost must pay the green tax and its total costs exceed the marginal cost, the difference is transferred to the rest of the generating plants that extract energy from the system. Therefore, the tax does not charge 100% of the CO_2 emissions to the emitting sources since it is being compensated by all the generating plants (including renewables technologies) [14].

During the first year of execution of Law 20 780, 191,2 MMUSD were collected, and 94,8% are from the generation companies' segment. Of the total collected money, the renewable generation plants paid 0,9% of the total compensation. For the year 2021, 183,8 MMUSD were cashed, of which 95,7% are associated with payments made by generating companies.

One proposal to be evaluated is to consider the green tax within the merit order of the generating plants, thus the thesis work of Rodrigo Bórquez [15] evaluated the social and environmental impact and analyzes the cost-benefit of four different scenarios under the PLP modeling to include the green tax in the marginal pricing of the system under a dry hydrology. Among the main results, the scenario of considering the green tax within the marginal cost obtained an incremental cost of the system close to MMUSD 120,1 (13% additional to the base scenario). The determination of the Net Social Benefit for the scenario of incorporation of the Green Tax in the marginal pricing system poses a negative result of MMUSD -126,8. Which means that the evaluation of this measure does not meet the economic viability criteria to proceed with its recommendation. However, under this scenario, it is possible to see benefits due to the reduction of local pollutants that constitute concrete evidence of the positive impact of this instrument, especially in provinces with a higher rate of impact due to atmospheric pollution, such as the provinces of Huasco and Conception.

Therefore, for the closure of coal-fired power plants to materialize within a period that does not affect the security of the National Electric System and without increasing the consumption of other fuels, it is necessary to identify enabling and conditioning measures to maintain the system economically efficient and adapted on demand, which also ensure the security and quality of the service. In this context, the study carried out by ACERA [16] identifies the need to develop new generation, storage, and transmission reinforcement capacity to carry out this replacement efficiently, maintaining the supply of demand at a minimum cost. In addition to the expected 10 GW of projects under construction and development expected to enter the SEN, an additional 8 GW of emerging technologies such as CSP, pumped hydro, and Battery Systems (BESS) are required to replace coal units between the period 2021 and 2025, and 1,1 GW is required in storage systems. On the other hand, regardless of the year of retirement of the coal-fired plants, the importance and convenience of developing solar energy near the sources of consumption and a strong wind development throughout the country is observed, concentrated in the Taltal area. Therefore, in case the system by 2025 is not adapted in terms of generation and additional storage, the system will increase generation based on fossil fuels (mainly diesel) reaching six times what is used in the year 2020, increasing the cost of the system close to 100 USD/MWh and consequently, increasing the level of total CO_2 emissions even higher than the case where not all coal plants are withdrawn.

Consequently, there is still nothing in sight that satisfies with the "polluter pays" principle of responsibility and that seeks to generate behavioral changes in those responsible for emissions and reduce their impacts.

5. Conclusion

This work has identified that the current LCOE has a reduction of approximately 16% compared to 2020 studies for the same location, which is mainly due to improved local knowledge about the technology and the entry of new players into the CSP market.

The second major finding was that including the green tax in the merit order does not produce the desired effect, since it produces a negative net social benefit, making the national electricity system more expensive, Unaligned with the principle of least-cost operation of the power supply system. A further study could assess the effect of measures such as: determining a percentage per hourly block of participation of long-term energy storage (LDES) technologies, such that it results in a positive net social benefit, fulfilling the “polluter pays” principle.

Data availability statement

There is no relevant additional data to this article beyond the presented content.

Author contributions

Conceptualization, M.C., C.H., Investigation, C.H., Methodology M.C, C.H., Programming C.H., Writing - original draft C.H. and C.F., Writing - review & editing, M.C., Supervision, M.C. and F.D.

Competing interests

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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References

1. A. Marzo, A. Salmon, J. Polo, J. Ballestrín, G. Soto, G. Quiñones, J. Alonso-Montesinos, E. Carra, M. Ibarra, J. Cardemil, E. Fuentealba and R. Escobar, "Solar extinction map in Chile for applications in solar power tower plants, comparison with other places from sunbelt and impact on LCOE," *Renewable Energy,* pp. 197-211, 2021. https://doi.org/10.1016/j.renene.2021.01.126
2. Gestion, "Agencia AFP," AFP, 30 June 2019. [Online]. Available: https://gestion.pe/economia/astroturismo-pleno-auge-chile-pais-mejores-cielos-planeta-271722-noticia/. [Accessed 8 April 2022].
3. Asociación de Concentración Solar de Potencia (ACSP), "INFORME DE COSTOS CSP - PELP 2023-2027," ACSP, Santiago, 2021.
4. National Renewable Energy Laboratory, System Advisor Model, 2014.
5. C. Hernández, R. Barraza, A. Saez, M. Ibarra and D. Estay, "Potential Map for the Installation of Concentrated Solar Power Towers in Chile," *Energies,* vol. 13, no. 9, p. 2131, 2020. https://doi.org/10.3390/en13092131
6. J. Hernández-Moro and J. M. Martinez-Duart, "Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution," *Renewable and Sustainable Energy Reviews,* vol. 20, pp. 119-132, 2013. https://doi.org/10.1016/j.rser.2012.11.082

7. R. T. Rivas and J. M. Cardemil, "Assessment of the contribution of carbon credits for the competitiveness of concentrating solar power plants in Chile," *Revista chilena de ingeniería,* vol. 23, no. 4, pp. 609-621, 2015.
8. R. Musi, B. Grange, S. Sgouridis, R. Guedez, P. Armstrong, A. Slocum and N. Calvet, "Techno-economic analysis of concentrated solar power plants in terms of levelized cost of electricity," *AIP Conference Proceedings,* vol. 1850, no. 1, p. 160018, 2017. https://doi.org/10.1063/1.4984552
9. I. Purohit and P. Purohit, "Techno-economic evaluation of concentrating solar power generation in India," *Energy Policy,* vol. 38, no. 6, pp. 3015-3029, 2010. https://doi.org/10.1016/j.enpol.2010.01.041
10. Energía Abierta Beta, "Capacidad Instalada," Capacidad total instalada, 05 July 2022. [Online]. Available: http://energiaabierta.cl/visualizaciones/capacidad-instalada/. [Accessed 07 July 2022].
11. Generadoras de Chile, "Generación eléctrica en Chile," March 2022. [Online]. Available:http://generadoras.cl/generacion-electrica-en-chile#:~:text=El%20mercado%20el%C3%A9ctrico%20chileno%20est%C3%A1,del%20Norte%20Grande%20(SING).&text=A%20marzo%20de%202022%20cuenta%20con%20una%20capacidad%20instalada%20de%2031.706%20MW. [Accessed 07 July 2022].
12. Biblioteca del Congreso Nacional de Chile, "Reforma tributaria que modifica el sistema de tributación de la renta e introduce diversos ajustes en el sistema tributario.," BCN, 29 September 2014. [Online]. Available: http://bcn.cl/2p5bm. [Accessed 07 July 2022].
13. Chile Sustentable, "Impuesto Verde: Una de las alternativas tributarias para reducir la emisión de contaminantes en la Industria y avanzar hacia la Descarbonización," Chile Sustentable, 17 June 2022. [Online]. Available: https://www.chilesustentable.net/2022/06/impuesto-verde-una-de-las-alternativas-tributarias-para-reducir-la-emision-de-contaminantes-en-la-industria-y-avanzar-hacia-la-descarbonizacion/. [Accessed 07 July 2022].
14. Chile Sustentable, "Minuta Impuesto Verde," April 2019. [Online]. Available: http://www.chilesustentable.net/wp-content/uploads/2019/04/. [Accessed 07 July 2022].
15. R. Bórquez, Análisis de impacto económico y social de la inclusión del impuesto verde en la determinación del costo marginal de la energía eléctrica, Santiago de Chile: Tesina - Magister en Economía Energética, 2019.
16. ACERA, Análisis y propuesta de una ruta de referencia para alcanzar cero emisiones en el sector de generación de energía eléctrica en Chile, 2022.