The Life Cycle Sustainability Indicators for Electricity Generation in Chile: Challenges in the Use of Primary Information

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Abstract The need to get an appropriate quantification of the sustainability indicators involves the use of site-specific information that could come from several sources, affecting its quality. This study analyses the quality and sources to build eight environmental, seven social and four economic indicators for eight electricity generation technologies in 2005, 2009 and 2015 as reference years, following the ISO 14.040-44:2006 life cycle assessment approach. The results show for the three dimensions important differences among the periods, reaching over 400% of reduction in 2015 in case of acidification for coal power plants, thanks to environmental regulations. For levelized electricity cost and corruption index, the variations reach around 40% and 30%, mainly for fossil fuel-based power plants. These changes support the need to have a centralized, reliable and accurate data system of registration, in order to contribute to the sustainability of the electricity system in Chile.

1 Introduction

The need to get an appropriate quantification of the sustainability indicators involves the use of site-specific information [1]. This information could come from several sources and sometimes is barely systematized and highly heterogenous, being its quality and consistency a matter of concern [2]. Due to the increasing environmental, economic and social requirements, more data are available to model the potential impacts profile. In particular, the power plants of electricity generation in Chile report continuously their air and water emissions, as well as the hazardous waste

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generated from their process, and from those were developed several accurate reports assessing the environmental performance [3–6]. Nevertheless, the results could be a source of more questions about the data quality, such as the traceability or the methodological approach to measure mass fluxes [1, 2, 7]. In the same way, the economic profile is well-known data for experts and investors, but is not always open and available for researchers. The social indicators are still under development and the data is usually scattered. For these reasons, just a few studies had covered jointly the environmental, economic and social dimensions [8–12].

As was reported by Laurent and Espinosa [13] is relevant to study the variability of the environmental performance at the country level, exploring the opportunity to analyse the annual environmental, economic and social performance, just in case to have enough reliable information. This analysis could bring information about the data sources, the quality needed and the potential effect of the assumptions. Moreover, in the case of developing countries, this analysis could be helpful to policy-makers to evidence the legal and regulatory needs to improve the current report of projects.

2 Goal and Scope

The aim of this work is to contribute to the discussion about the use of primary information reported directly from electricity generation power plants, to get an appropriate pool of environmental, economic and social indicators for the electricity generation in Chile. The scope of this work is cradle to gate for the environmental aspects, while for social and economic are covered the direct processes, due to the lack of information.

For environmental issues was included the whole electricity generation process, from the materials and fuel extraction from natural sources to the decommissioning stage, including the transport, infrastructure and operation specific for each year assessed (see Fig. 1). Economic indicators were developed based on local information for technologies investments, for each year, and reported as “blackbox”, without the possibility of disaggregating by stage. In the same sense, the social

Fig. 1 System boundaries of the electricity generation in Chile considered in this work

information was obtained from several sources and represents different stages of the process (e.g. employment is associated with infrastructure and operation, while import dependency is associated with the whole process).

3 Methodological Procedure

This work was developed following the ISO 14.040-44:2006 [14, 15] approach for life cycle assessment. The electricity generation power plants covered in this work were selected to build a set of eight environmental, four economic and seven social indicators, following a life cycle approach applied to eight electricity generation technologies, coal, diesel, natural gas, biomass, wind power, solar photovoltaic (PV), run of river and reservoir, in Chile. The temporal coverage includes 10 years, using specific data for 2005, 2009 and 2015. The technologies assessed cover more than 99.5% of the current installed capacity in Chile, and the geographical coverage only includes the continental territory, excluding Patagonia. The electricity generation produced by technology for the period analysed is presented in Table 1.

3.1 Definition of Environmental, Economic and Social Indicators

The environmental indicators have been calculated from CML 2000 mid-point impact model. Several studies have worked with this impact model to represent the damage over different categories. Some categories are associated with environmental impacts and another with social impacts, as is detailed in respective subsection.

Eight environmental indicators, namely, ozone layer depletion potential (ODP), photochemical oxidation potential (POP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity

Table 1 Electricity generation in Chile in 2005, 2009 and 2015

Technology	Electricity generation by source (GWh/y)		
	2005	2009	2015
Coal	8813	15,625	28,613
Diesel	1113	1395	2862
Natural gas	14,681	1,444,038	10,807
Biomass	518	968	1931
Wind power	–	61	2103
Solar PV	–	–	1373
Reservoir	14,801	13,921	11,616
Run of river	10,673	10,633	12,283
Total	50,599	56,641	71,588

potential (FAEP), marine aquatic ecotoxicity potential (MAETP) and terrestrial ecotoxicity potential (TEP) impacts were assessed in this study, on the basis of previous work [3, 4]. These indicators were calculated following the ISO 14.040-44:2006 standards for life cycle assessment [14, 15], using the CML 2000 v.2.05 mid-point impact models [16], with the computational support of SimaPro v.7.3.3 software [17].

On the other hand, four indicators were used to address economic issues, namely, total capital cost (TCC), levelized electricity cost (LEC) and fuel sensitivity price (FSP) as proposed by [18], while total annualized cost (TAC) was considered from the definition brought by [9]. Finally, seven indicators related to social issues were estimated. These issues were addressed by [18] and categorized as follows:

- Energy security, measured as import dependency (ID), imported fuels potentially avoided (IFPA) and diversity of fuel supply (DFS)
- Provision of employment (PE)
- Intergenerational issues, measured as human toxicity (HT) and abiotic depletion (ADP)
- Local community impacts measured as corruption index (CI)

Every indicator was estimated by technology and by year totalizing 399 indicators specific for Chilean electricity situation.

3.2 Data Sources, Quality and Assumptions

The data were obtained mainly from primary open sources. They were several governmental offices and institutions, which have been implemented a transparency system of data registration, mainly driven by environmental control regulations. In this sense, was possible to get reliable data from these sources to build the most part the indicators reported [19–24]. Some others were obtained from studies [25], international reports [26] and assumptions.

The most part of the assumptions were addressed to economic and social indicators. Particularly, all the costs were corrected to 2015 value, considering the inflation, in order to compare the decade's values. Due the lack of data for cost of renewables investment in Chile, they were assumed from international values for the same technology [26]. For corruption index, the data were considered using the perception index for the respective year, and the mix of imported fuels.

3.3 Variation on Indicator Values

For every indicator, the variation with respect to the 2015 value was estimated, in order to represent a better or worst situation in the past compared with the current. To quantify this, the use of a percentage of variation is proposed defined by Equation 1.

$$\%variation = \left(\frac{Indic.value_{2005} - Indic.value_{2015}}{Indic.value_{2015}} \right) * 100 \tag{1}$$

This percentage represents the pathway that every single indicator has followed during this last decade. Depending of the accuracy and representability of the information reported for each indicator, this variation could be relevant or null.

This variation does not apply to solar PV during 2005 and 2009, as well as for wind power during 2005 due the lack of contribution to the electricity generation from these sources in those years.

4 Results and Discussion

The results are presented in terms of a general analysis of the data quality followed by the main variation of the environmental, economic and social indicators among the period covered between 2005 and 2015.

4.1 Analysis of Data Quality and Sources

The analysis of the data quality is based on the description of the five aspects included in the pedigree matrix. The description is presented in Table 2.

From the table above, it is possible to identify that only reliability could be a source of uncertainty, while the rest are well covered. However, the data

Table 2 Description of data quality based on pedigree matrix aspects

Pedigree aspects	Description
Reliability	The most part of environmental, economic and social data were obtained from primary source, with exception of infrastructure of run of river, diesel and solar PV, which were complemented with ecoinvent data. For the economic indicator, only the costs for biomass were obtained from foreign source in 2005 and 2009
Completeness	All the process stages were covered in the simulation and there are no missing data
Temporal coverage	Each environmental, economic and social data was specific for each year and not average was used covering more than 1 year
Geographical coverage	The continental territory in Chile was completely covered with the exception of Patagonia. The overseas territory was not included
Technological coverage	The 99.5% of installed capacity of each year was covered in this study, upgrading annually the electricity generation, the conversion efficiency, air emissions, prices and corruption and perception index

assumptions are based on verified information, becoming the main constraints the source and its location instead of the availability of data.

In this case, the location of data process for the environmental profile by technology was based on sources from the Environmental and Energy Ministry and official agencies. This information must be reported because it is mandated by law. On the contrary, the information for the economic profile were obtained from different and heterogeneous sources, such as official agencies, international reports and specific studies, avoiding the systematization of the consultancy and the respective updating. The Economic Ministry has no data about these issues and the Energy Ministry has only information about the cost of investment just for some years and not enough disaggregated to be consistent with the life cycle approach. In fact, this information could be really well-known by investors but still unknown by the researchers. More dramatic is the availability of the social information, with no official institution or agency controlling these aspects and main part of the information obtained from sources related with environmental issues. Currently, scatter and spot information are available determining the capacity to include more and better social indicators.

Everything was possible only thanks to a very detailed and continuously updated knowledge about current instruments of central information report, which has been very dynamic and improved. For this reason, the development of a detailed work like this could be a field of close relation with the central authorities, in order to have a constant validation and evidence the future needs.

4.2 Environmental Indicators

The environmental indicators had important changes during the period, mainly due to changes for conversion efficiency by technology and changes in the environmental regulations. The effect of the conversion efficiency is shown in Fig. 2, for natural gas mainly, where in 2005 and 2009 the acidification potential (ACP) was 10% and 22% higher than in 2015, respectively. On the other hand, the effect of new environmental regulations over the environmental profile of the thermal technologies is clearly exposed in the behaviour of acidification for coal power plants in 2005 and 2015. The reduction of this indicator was over 400%, thanks to a specific regulation for thermoelectric plants, due to its high emission levels and poor abatement systems.

The rest of the environmental indicators present changes like that representing the specific annual situation of each technology [3]. Since these relevant changes in each indicators, it worth to keep constantly evaluated the process data reported in the environmental system, in order to validate them and contribute with a more accurate and transparent central information repository.

Fig. 2 Variation percentage of acidification environmental indicator in 2005 and 2009 in relation to 2015

4.3 Economic Indicators

Economic indicators are very sensitive with market constrains; for this reason, the need to count with updated information is vital. As is possible to see from Fig. 3, the leveled electricity cost presents a relevant variation in 2005 and 2009 relative to 2015 for all technologies. In fact, thermal power plants present higher values in 2015 than in 2005 and 2009, reaching for coal -36% and -30%, respectively. Due to the uncertainty related to the cost of investment for biomass, the fluctuations are very wide. The reduction of the LEC of wind power among 2009 and 2015 presents the trends in the international markets, where the cost of this technology has decreased.

The important changes in the economic indicators reflect the need to have an updated source of information based on local restrictions, where it could be systematized in order to contribute to an accurate economic analysis. The use of average values from other countries are too vague, for the same reason that is not convenient to consider the economic allocation for the environmental burdens [14, 15].

Fig. 3 Variation percentage of levelized electricity cost economic indicator in 2005 and 2009 in relation to 2015

4.4 Social Indicators

The social indicators present an important variation among the period. In Fig. 4 is shown the corruption index (CI) performance, which is very sensitive for coal, natural gas, diesel and biomass, mainly due to the importance of fuel. In the case of biomass, changes in corruption and perception index in 2005 and 2009 explain the different trends through those years. In the same sense, coal presents the same different trends. While in 2005 coal was imported from Australia and Canada mainly, in 2009, there was a change as to the importing country which was exclusively done by Colombia, to be finally shared in 2015 with USA and Australia.

In the same sense as environmental and economic indicators, social indicators present a dynamic behaviour which could be dramatically different when the conditions of technologies present changes through time.

These evidences are key to sustain the need to have a data depository which can be systematized, appropriate, reliable and accurate, in order to take advantage of the current process data report, to shift them to a sustainable platform with updated and continuously improved data accuracy and to assess the global performance, specifically, of the electricity sector in Chile.

Fig. 4 Variation percentage of corruption index social indicator in 2005 and 2009 in relation to 2015

5 Conclusions

The knowledge about the local environmental reporting system could be really helpful in the case of build a database with primary data regarding the life cycle approach for processes. This system for Chile is still a matter of development, but results like these could be an important input in order to address improvements to the current system. Nevertheless, the social and economic issues are still scattered and were obtained from heterogeneous sources, which are not necessarily the best option for a detailed assessment. This is closely related with the legal need to report the operational performance instead of the global performance.

Understanding sustainability as an equilibrium between environmental, social and economic dimensions, the development of the electric sector ought to be driven to improve data quality, systematizing the reports to check and manage the global performance of the sector.

This critical analysis could be useful for decision-makers and countries in the pathway of development, which are implementing environmental open reports with perational data, specifically for the electricity generation.

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