*Cómo citar este artículo: J. G. Lassio, et al, "Life cycle sustainability assessment of power generation espansion: the current and future scenarios in Brazil" Revista Ingeniería, Investigación y Desarrollo, vol. 21 (2), pp.73-80, julio. 2021.*

*DOI: https://doi.org/10.19053/1900771X.v21.n2.2021.14272*

# LIFE CYCLE SUSTAINABILITY ASSESSMENT OF POWER GENERATION EXPANSION: THE CURRENT AND FUTURE SCENARIOS IN BRAZIL

## Análisis de sostenibilidad del ciclo de vida de la expansión de energía en Brasil

*João Gabriel Lassio[1-2], Denise Matos[1-2], David Castelo Branco[1], Alessandra Magrini[1]*
*[1]Federal University of Rio de Janeiro, The Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering, Energy Planning Program, Brazil. Institutional [2]Electrical Energy Research Center, Energy Optimization and Environment Department, Brazil. Institutional Email: [1]secretaria@ppe.ufrj.br, [2]dea@cepel.br*

*(Recibido 19 de noviembre de 2021 y aceptado 02 de diciembre de 2021)*

**Abstract**
The sustainable development paradigm has been encouraging the current worldwide transition from fossil fuels to renewable energy sources and a more balanced approach to the social-environmental concerns against economic hegemony, which implies changes in how decision-makers design the future electricity system. In this context, this paper explores the integration of the Life Cycle Sustainability Assessment (LCSA) with a Multicriteria Decision Making (MCDM) method, named Simple Multi-Attribute Rating Technique Exploiting Ranks (SMARTER), in order to analyze and compare the sustainability performance of the current electricity mix with different future scenarios in Brazil, reported by The Brazilian Ten-Year Energy Expansion Plan 2027. This analysis considers nine criteria distributed into environmental, social, and economic dimensions of sustainability obtained from different sources, such as literature, the Ecoinvent 3.5 database, and calculated by ReCiPe 2016 and USEtox 2 methods. According to the results, the current electricity mix presents the best social and economic performance, and its environmental performance will enhance in the future, mainly due to the expansion of some renewable energy sources. Concerning the future scenarios investigated, the results indicate that those with greater participation from these energy sources are associated with the best sustainability performance. However, it is worth pointing out that these results do not represent the most suitable Brazilian electricity mix path. Besides the criteria considered in this paper, it is influenced by other factors, such as technical, geographical, and national policy. Furthermore, assuming different suppositions and system boundaries for energy sources and technologies might significantly vary our findings.

**Keywords:** *life cycle sustainability assessment, energy planning, power generation, sustainability.*

**Resumen**
El paradigma de desarrollo centrado en la sostenibilidad no solo ha impulsado la actual transición energética hacia las fuentes renovables, sino que también se ha convertido en una prioridad para tener en cuenta todas aquellas cuestiones socio-ambientales a lo largo de la cadena de generación eléctrica, lo que implica una actualización de la forma en la que se planifica la expansión del suministro eléctrico en el futuro. En este contexto, este artículo explora la integración del Análisis de Sostenibilidad del Ciclo de Vida (ASCV) con un método de Análisis de Decisiones Multicriterio (ADM), denominado Técnica de Calificación de Atributos Múltiples Simples (SMARTER), para evaluar la sostenibilidad de la matriz eléctrica actual y de los escenarios futuros en Brasil, proyectados por el Plan Decenal de Expansión Energética de Brasil 2027. El análisis se realiza de acuerdo con nueve criterios distribuidos en las dimensiones ambiental, social y económica. Los resultados indican un mejor desempeño social, económico y ambiental de la matriz eléctrica nacional actual, así como, en sus escenarios futuros, principalmente, debido a la expansión de la participación de algunas fuentes de energía renovables.

Con respecto a los escenarios futuros, aquellos con mayor participación de estas fuentes se asocian con el mejor desempeño en materia de sostenibilidad. No obstante, estos resultados no pretenden señalar el camino más adecuado para el Parque Nacional de Generación Eléctrica, ya que, para ello, también es necesario tomar en cuenta otros factores, además de los considerados en este artículo, como son los macroeconómicos, técnicos, de ubicación, políticas públicas, etc.

**Palabras clave:** *análisis de sostenibilidad del ciclo de vida, planificación energética, generación de poder, sostenibilidad.*

## 1. INTRODUCTION

The concept of sustainable development has promoted the current global transition from fossil fuels to renewable energy sources, as well as a more balanced approach to social-environmental concerns in the face of economic hegemony [1]. However, these trends might result in potential challenges to developing countries like Brazil. This is not only because advancing toward sustainability faces which are additional obstacles for these countries, but also because they are the leading drivers of the global energy supply growth [2]. In this sense, for instance, Brazil has experienced an average annual increase of more than 2% in its energy supply in the last decade alone. For the following ten years, a similar evolution is expected [2].

In this context, the Brazilian energy policy forecasts an introduction of renewable energy sources in the national electricity mix. As a result, their already high shares are projected to increase even more, from 84% to 87% by 2030 [2]. Energy transitions, combined with current sustainability requirements, which imply changes in how decision-makers design the future electricity system [1]-[3].

The present paper is part of a comprehensive project concerned with incorporating socio-environmental aspects in long-term planning models for the electricity generation expansion in Brazil. With this aim in mind, this paper corresponds to its starting point by exploring the integration of the Life Cycle Sustainability Assessment (LCSA) with a Multicriteria Decision Making (MCDM) method named Simple Multi-Attribute Rating Technique Exploiting Ranks (SMARTER) [4] to assess and compare the sustainability performance of the current electricity mix with different future scenarios reported by The Brazilian Ten-Year Energy Expansion Plan 2027 [5].

LCSA is based on the life cycle approach that is especially advantageous for the most promising renewable energy sources because the most of their socio-environmental impacts are dispersed throughout their whole production chains rather than are concentrated in the energy generation stage [6].

Previous studies have yielded some important insights into life cycle-based sustainability assessments of the penetration of renewable energy sources and future energy scenarios at regional and national scales. Specifically, Hong and colleagues [7] examined the sustainability of electricity generation scenarios in South Korea, taking into consideration their environment, social, and economic aspects and employing an MCDM method. In [8], the authors provide a methodology based on the life cycle approach to assess the sustainability of different energy systems against environmental, social, and economic issues. At the same time, these researchers propose the integration of life cycle-based tools with an MCDM method. By the other hand, in this study, [9] authors compared the 13 different technologies for energy generation and ten representative scenarios in the United States.

In this research, the authors used an MCDM method and considered eight sustainability criteria, most of them based on the life cycle approach. Finally, in [10] authors carried out a life cycle-based analysis of the sustainability of different scenarios for the Pakistani energy sector, taking into account seven energy sources and environmental, social, and economic aspects. Although life cycle thinking is widely used worldwide, it is still seldom employed in Brazil [11], [12], and scant attention has been paid to the sustainability of the Brazilian energy sector from a life cycle perspective.

## 2. **METHODOLOGY**

*2.1. Life Cycle Sustainability Assessment*

LCSA entails evaluating potential environmental, social, and economic negative impacts and benefits in decision-making processes for more sustainable products and services over their whole life cycle. However, it is worth mentioning that LCSA, unlike Life Cycle Assessment (LCA), does not have a standardized methodology [13], [14].

In this context, this study is based on the Kloepffer [15] approach, which integrates LCA, Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC) (see Figure 1) to analyze the environment, social, and economic dimensions of sustainability [16] (see Figure 1). It noted that these three life cycle-based tools are according to the ISO 14040 [17] stages; they are: (i) goal and scope definition, (ii) life cycle inventory (LCI) analysis, (iii) life cycle impact assessment (LCIA), and (iv) interpretation. Moreover, they have similar viewpoints and objectives [13]-[18], [19].

It should be pointed out that performing an LCSA poses a number of methodological and practical challenges, including the lack of data and methods; the need for efficient ways of communicating its findings; the subjectivity of sustainability indicators, particularly the social ones; and the integration of its results in order to express the degree of sustainability of a product or service [14]-[20], [21].

Given this scenario, there is a growing body of research on LCSA employing multiple-criteria decision analysis (MCDA) methods [21]. For example, the SMARTER technique [4] is a well-known subjective weighting MCDA method that ranks different alternatives.

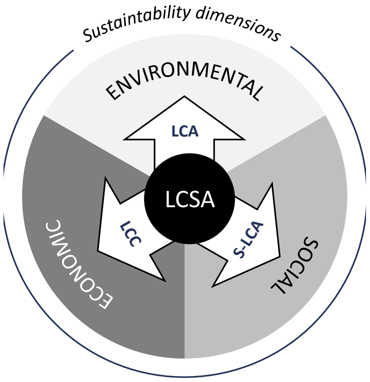


**Figure 1.** Scheme of LCSA framework

*2.2. The SMARTER method*

The SMARTER (Simple Multi-Attribute Rating Technique Exploiting Ranks) technique [4] is a linear additive MCDA method. Objective weighting approaches cannot describe the evaluation of diverse alternatives as clearly as this well-known subjective weighting methodology can. In addition, it can help interpret the outcomes of sustainability analyses by creating sustainability indicators.

Figure 2 shows the main steps of the SMARTER method to ranking alternatives. Following this framework, we first (i) define weights for each alternative against sustainability indicators (Equation 1), (ii) the scores for each alternative against sustainability dimensions (Equation 2), and finally, (iii) the sustainability index for each alternative (Equation 3) [4]-[22].

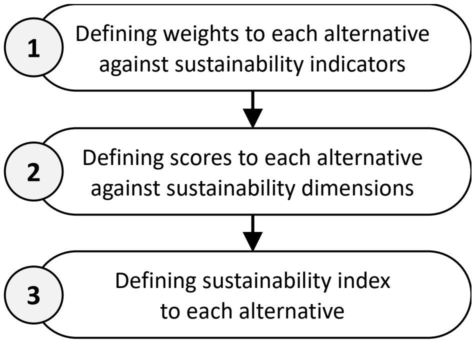


**Figure 2.** Main steps of the SMARTER method to ranking alternatives.

$$w_k = \left(\frac{1}{N}\right) \times \sum_{i=k}^{N} \left(\frac{1}{i}\right) \qquad (1)$$

Where, $Wk$ is the weight of the indicator for the alternative $k$, $N$ is the number of the alternatives considered in the analysis, $w_1 + w_2 + ... + w_k = 1$, and $w_1 \geq w_2 \geq ... \geq w_k$.

$$W_k^d = \sum_{indicator} W_k \qquad (2)$$

Where, $W_k^d$ corresponds to the total score reflecting the performance of technology $k$ on the sustainability dimension ***d*.**

$$SI_k = \sum_{dimension} \left(\frac{1}{N_d} \times W_k^d\right) \qquad (3)$$

Where, $SI_k$ corresponds to the alternative specific sustainability index, and $N_d$ is the number of indicators for dimension $d$.

*2.3. Analyzing the sustainability of Brazilian electricity generation scenarios*

To support the sustainability of the ongoing energy transition in Brazil, this paper focuses on the current electricity mix and the future scenarios projected by The Brazilian Ten-Year Energy Expansion Plan 2027 [5]. This document relates to the Brazilian energy sector's most comprehensive plan. From the perspective of the Brazilian government, it provides specific information on power generation capacity increases, investment forecasts, and fuel production plans for the next ten years in the country [5].

This analysis considers nine criteria distributed into environmental, social, and economic dimensions of sustainability, which were gathered from different sources, such as literature [23]-[27] and the Ecoinvent 3.5 [28] database, and calculated using the ReCiPe 2016 [29] and USEtox 2 [30] methods in the SimaPro 9.0 LCA software. In addition, the SMARTER method [4], based on a linear additive model, supports the interpretation of results by formulating sustainability indicators.

Table 1 shows the current and the nine future scenarios considered in our analysis, as published by the Brazilian Ten-Year Energy Expansion Plan 2027 [5]. In this, note that the current mix, as well as scenarios 3, 8, and 9, present the most significant shares of renewable energy sources. In contrast, scenarios 2, 5, and 6 have the highest percentages of non-renewable energy sources. It is worth mentioning that scenarios 3 and 4 assume a coal expansion [5].

**Table 1** Scenarios assessed in our analysis

| Scenario | Renewables | Non-Renewables |
|---|---|---|
| Current | 85.3% | 14.7% |
| Scenario 1 | 79.6% | 20.4% |
| Scenario 2 | 78.6% | 21.4% |
| Scenario 3 | 80.7% | 19.3% |
| Scenario 4 | 79.5% | 20.5% |
| Scenario 5 | 79.2% | 20.8% |
| Scenario 6 | 79.2% | 20.8% |
| Scenario 7 | 79.6% | 20.4% |
| Scenario 8 | 80.8% | 19.2% |
| Scenario 9 | 81.2% | 18.8% |

The sustainability performance of these ten scenarios were assessed considering the generation of 1.0 kWh and system boundaries that encompass the life cycle stages from the extraction of the raw materials to the end-of-life of the power plants. Based on this, Table 2 lists the set of sustainability criteria considered in this analysis. The environmental dimension comprises global warming (GWP), freshwater eutrophication (FWT), land use (LAU), and water consumption (WAT). The social dimension of sustainability is assessed through job creation (JOB), human toxicity (HTC and HTnC), and intergenerational equity (INE). Finally, regarding the concerns of the economic dimension, our analysis addressed the levelized cost of energy (LCOE).

**Table 2.** Sustainability criteria considered in our analysis

| Impact category | Unit | Source |
|---|---|---|
| *Environment* | | |
| Global warming | kg $CO_2$ eq. | [28], [29] |
| Freshwater ecotoxicity | PAF.m$^3$.day | [30] |
| Land use | m$^2$a crop eq. | [28], [29] |
| Water consumption | m$^3$ | [28], [29] |
| *Social* | | |
| Job creation | jobs.year | [23] |
| Human toxicity (carc.) | cases | [30] |
| Human toxicity (non-carc.) | cases | [30] |
| intergenerational equity | kg Cu | [28], [29] |
| *Economic* | | |
| Levelized cost of energy | USD/kWh | [24]–[27] |

## 3. RESULTS & ANALYSIS

Table 3 presents the results of the LCIA step for the ten different scenarios examined. Given these results, it was possible to rank each scenario within each sustainability criterion, as illustrated in Figure 3. For instance, we can observe that the current electricity mix performs better in five sustainability criteria: global warming, human toxicity (non-carcinogenic), intergenerational equity, and levelized cost of energy. On the other hand, it is relevant noting that the current electricity mix presents two extremely negative performances in land use and water consumption criteria. Additionally, scenario 3 delivers the worst performance in freshwater eutrophication and human toxicity (carcinogenic and non-carcinogenic).

Following the methodology employed in this paper, we used this rank to define the scores for each scenario against sustainability dimensions and then their sustainability index through Equations 2 and 3, respectively (see Table 4).

It can be inferred from Table 4 that scenarios 1, 2, and 7 perform better in the environmental dimension, while scenarios 3, 4, and 6 are the worst. In addition, concerning the social dimension, the current mix and scenarios 5 and 9 present the best performances, whereas scenarios 3, 6, and 8 present the worst performances. Furthermore, for the economic dimension, the current mix and scenarios 8 and 9 present the most significant scores; and scenarios 4, 5, and 6 present the lowest ones. Finally, the current mix and scenarios 1 and 9 have the better sustainability index. In contrast, scenarios 3, 4, and 6 present the lowest sustainability performance.

**Table 3.** LCIA results

| # | GWP | LAU | WAT | FWT | HTC | HTn-C | INE | JOB | LCOE |
|---|---|---|---|---|---|---|---|---|---|
| | kg $CO_2$eq. | m$^2$a crop. eq. | m$^3$ | PAF. m$^2$.day | cases | cases | Kg Cu | jobs. year/ MW | USD/kWh |
| C | 1.9210$^{-1}$ | 1.2010$^{-2}$ | 2.0910$^{-2}$ | 5.7710$^{2}$ | 6.1210$^{-9}$ | 1.4710$^{-2}$ | 3.7810$^{-5}$ | 52.79 | 39.7110$^{-3}$ |
| 1 | 2.0310$^{-1}$ | 1.1010$^{-2}$ | 1.7610$^{-2}$ | 5.2110$^{2}$ | 5.3310$^{-9}$ | 2.0710$^{-2}$ | 4.3910$^{-5}$ | 48.74 | 48.1610$^{-3}$ |
| 2 | 2.0710$^{-1}$ | 1.1110$^{-2}$ | 1.7110$^{-2}$ | 5.0410$^{2}$ | 5.1610$^{-9}$ | 2.2010$^{-2}$ | 4.4010$^{-5}$ | 48.56 | 49.3010$^{-3}$ |
| 3 | 2.0810$^{-1}$ | 1.1510$^{-2}$ | 1.8410$^{-2}$ | 9.0110$^{2}$ | 8.4510$^{-9}$ | 2.2110$^{-2}$ | 4.3610$^{-5}$ | 50.21 | 49.1910$^{-3}$ |
| 4 | 2.1410$^{-1}$ | 1.1410$^{-2}$ | 1.8210$^{-2}$ | 8.9910$^{2}$ | 8.3910$^{-9}$ | 2.0410$^{-2}$ | 4.4810$^{-5}$ | 50.33 | 50.2010$^{-3}$ |
| 5 | 2.0710$^{-1}$ | 1.1110$^{-2}$ | 1.7810$^{-2}$ | 5.3010$^{2}$ | 5.4010$^{-9}$ | 1.9110$^{-2}$ | 4.1910$^{-5}$ | 48.99 | 49.4310$^{-3}$ |
| 6 | 2.0410$^{-1}$ | 1.1410$^{-2}$ | 1.8410$^{-2}$ | 6.9910$^{2}$ | 6.2310$^{-9}$ | 1.8810$^{-2}$ | 4.8510$^{-5}$ | 49.95 | 49.5010$^{-3}$ |
| 7 | 2.0310$^{-1}$ | 1.1010$^{-2}$ | 1.7610$^{-2}$ | 5.2110$^{2}$ | 5.3310$^{-9}$ | 2.0710$^{-2}$ | 4.3910$^{-5}$ | 48.74 | 48.1610$^{-3}$ |
| 8 | 1.9510$^{-1}$ | 1.1210$^{-2}$ | 1.8010$^{-2}$ | 5.3010$^{2}$ | 5.4310$^{-9}$ | 2.1110$^{-2}$ | 4.5210$^{-5}$ | 48.85 | 46.3210$^{-3}$ |
| 9 | 1.9510$^{-1}$ | 1.1210$^{-2}$ | 1.7910$^{-2}$ | 5.2810$^{2}$ | 5.4210$^{-9}$ | 1.8110$^{-2}$ | 4.4310$^{-5}$ | 50.49 | 47.4410$^{-2}$ |

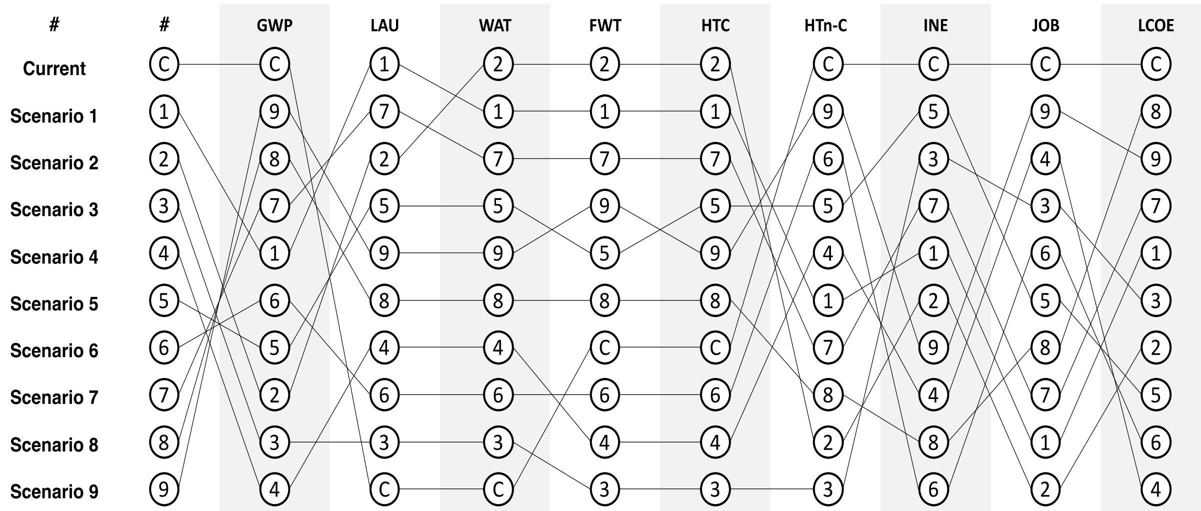


**Figure 3.** Ranking scenarios within each criterion

**Table 4**. Sustainability dimensions' scores and sustainability index

| # | Dimension of sustainability | | | Sust. |
|---|---|---|---|---|
| | Environ. | Social | Economic | Index |
| C | 0.3608 | 0.9266 | 0.2929 | 0.6147 |
| 1 | 0.7633 | 0.3631 | 0.0846 | 0.3662 |
| 2 | 0.7623 | 0.3886 | 0.0479 | 0.3356 |
| 3 | 0.0733 | 0.2725 | 0.0646 | 0.1510 |
| 4 | 0.1269 | 0.2822 | 0.0100 | 0.1123 |
| 5 | 0.3516 | 0.4766 | 0.0336 | 0.2407 |
| 6 | 0.1654 | 0.2711 | 0.0211 | 0.1302 |
| 7 | 0.5883 | 0.3340 | 0.1096 | 0.3401 |
| 8 | 0.3366 | 0.1672 | 0.1929 | 0.3188 |
| 9 | 0.4716 | 0.5183 | 0.1429 | 0.3904 |

These findings could be less surprising if we remember that the current mix and scenarios 1 and 9 present a high level of renewable energy sources, while scenarios 3 and 4 consider a coal expansion, as well as scenario 6, shows a low level of renewable energy sources.

Taken altogether, the data presented here provide preliminary evidence to suggest that renewable energy sources are associated with a better sustainability performance. Ultimately, considering that the current mix presents two extremely negative performances, more specifically in land use and water consumption criteria, we believe that this scenario cannot be established as the most sustainable one in relation to all scenarios considered.

## 4. CONCLUSIONS

Since the concept of sustainable development has encouraged the ongoing energy transition and a more balanced approach to social-environmental concerns in the face of economic hegemony, this paper investigated the sustainability of the current electricity mix with different future scenarios reported by The Brazilian Ten-Year Energy Expansion Plan 2027, by integrating of the LCSA with an MCDM method known as SMARTER.

The results yielded some interesting findings. According to them, the current electricity mix presents the best social and economic performance. Its environmental performance will enhance in the future mainly due to the expansion of some renewable energy sources. Furthermore, taking into consideration the future scenarios reported by PDE 2027, the results indicate that those with greater participation from these energy sources are associated with the best sustainability performance.

However, it is worth pointing out that these results do not represent the most suitable Brazilian electricity mix path. Besides the criteria taken into account in this paper, it is influenced by other factors, such as technical, geographical, and national policy. Furthermore, assuming different suppositions and system boundaries for energy sources and technologies might significantly vary our findings.

Our immediate future studies involve looking into the integration of LCSA with other MCDM methods and meeting the challenge of considering more social aspects. Finally, it is worth mentioning that several findings of this study warrant further discussion, such as the influence of energy sources' sustainability performances on the decision-making of the national energy sector.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Brazilian Council for Scientific and Technological Development (CNPq).

## REFERENCES

[1] A. Maxim, "Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis," *Energy Policy,* vol. 65, pp. 284–297, Feb. 2014, doi: 10.1016/j.enpol.2013.09.059.

[2] Brazil, "The Ten-Year Energy Expansion Plan 2030," Brasília, 2020.

[3] J. G. Lassio, A. Magrini, and D. Castelo Branco, "Life cycle-based sustainability indicators for electricity generation: A systematic review and a proposal for assessments in Brazil," *J. Clean. Prod.,* vol. 311, p. 127568, Aug. 2021, doi: 10.1016/j.jclepro.2021.127568.

[4] W. Edwards and F. H. Barron, "Smarts and smarter: Improved simple methods for multiattribute utility measurement," *Organ. Behav. Hum. Decis. Process.*, vol. 60, no. 3, 1994, doi: 10.1006/obhd.1994.1087.

[5] Brazil, "The Ten-Year Energy Expansion Plan 2027," Brasília, 2018.

[6] A. Laurent, N. Espinosa, and M. Z. Hauschild, "LCA of Energy Systems," in *Life Cycle Assessment,* M. Hauschild, R. Rosenbaum, and S. Olsen, Eds. Cham: Springer International Publishing, 2018, pp. 633–668.

[7] S. Hong, C. J. A. Bradshaw, and B. W. Brook, "Evaluating options for sustainable energy mixes in South Korea using scenario analysis," *Energy,* vol. 52, pp. 237–244, 2013, doi: 10.1016/j.energy.2013.02.010.

[8] E. Santoyo-Castelazo and A. Azapagic, "Sustainability assessment of energy systems: integrating environmental, economic and social aspects," *J. Clean. Prod.*, vol. 80, pp. 119–138, Oct. 2014, doi: 10.1016/j.jclepro.2014.05.061.

[9] S. J. W. Klein and S. Whalley, "Comparing the sustainability of U.S. electricity options through multi-criteria decision analysis," *Energy Policy,* vol. 79, pp. 127–149, Apr. 2015, doi: 10.1016/j.enpol.2015.01.007.

[10] M. Z. Akber, M. J. Thaheem, and H. Arshad, "Life cycle sustainability assessment of electricity generation in Pakistan: Policy regime for a sustainable energy mix," *Energy Policy,* vol. 111, no. September, pp. 111–126, Dec. 2017, doi: 10.1016/j.enpol.2017.09.022.

[11] O. C. Filho, N. L. S. Junior, and G. Luedmann, "A Avaliação de Ciclo de Vida como ferramenta para a formulação de políticas públicas no Brasil," Brasília, 2016. [Online]. Available: http://repositorio.ipea.gov.br/bitstream/11058/6685/1/td_2205.pdf.

[12] C. G. Souza, R. G. Barbastefano, and R. C. Teixeira, "Life cycle assessment research in Brazil: characteristics, interdiciplinarity, and applications," *Int. J. Life Cycle Assess.,* vol. 22, no. 2, pp. 266–276, Feb. 2017, doi: 10.1007/s11367-016-1150-5.

[13] W. Kloepffer, "Life cycle sustainability assessment of products," *Int. J. Life Cycle Assess.*, vol. 13, no. 2, pp. 89–95, Mar. 2008, doi: 10.1065/lca2008.02.376.

[14] J. Guinée, "Life cycle sustainability assessment: What is it and what are its challenges?," in *Taking Stock of Industrial Ecology,* R. Clift and A. Druckman, Eds. Springer, Cham, 2016, pp. 45–68.

[15] W. Kloepffer, "Life cycle sustainability assessment of

products (with Comments by Helias A. Udo de Haes, p. 95)," 2008, doi: 10.1065/lca2008.02.376.

[16] J. Elkington, "Cannibals with forks: The triple bottom line of sustainability," *New Soc. Publ.,* 1998.

[17] ISO, "ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework," *International Organization for Standardization.* International Organization for Standardization, 2006.

[18] UNEP, "Guidelines for Social Life Cycle Assessment of Products and Organizations 2020," 2020.

[19] D. Hunkeler, K. Lichtenvort, and G. Rebitzer, *Environmental Life Cycle Costing.* Boca Raton: CRC Press, 2008.

[20] J. B. Guinée *et al.,* "Life cycle assessment: Past, present, and future," *Environ. Sci. Technol.,* 2011, doi: 10.1021/es101316v.

[21] P. P. Kalbar and D. Das, "Advancing life cycle sustainability assessment using multiple criteria decision making," in *Life Cycle Sustainability Assessment for Decision-Making,* 2020.

[22] I. Khan, "Sustainability challenges for the south Asia growth quadrangle: A regional electricity generation sustainability assessment," *J. Clean. Prod.*, vol. 243, p. 118639, Jan. 2020, doi: 10.1016/j.jclepro.2019.118639.

[23] M. Ram, A. Aghahosseini, and C. Breyer, "Job creation during the global energy transition towards 100% renewable power system by 2050," *Technol. Forecast. Soc. Change,* vol. 151, p. 119682, Feb. 2020, doi: 10.1016/j.techfore.2019.06.008.

[24] M. Tolmasquim, *Renewable energy: hydro, biomass, wind, solar, ocean.* Río de Janeiro, 2016.

[25] K. Mongird *et al.,* "Energy storage technology and cost characterization report," 2019.

[26] M. Tolmasquim, *Thermoeletric energy: natural gas, biomass, coal, and nuclear.* Río de Janeiro, 2016.

[27] O. Schmidt, S. Melchior, A. Hawkes, and I. Staffell, "Projecting the Future Levelized Cost of Electricity Storage Technologies," *Joule,* vol. 3, no. 1, pp. 81–100, Jan. 2019, doi: 10.1016/j.joule.2018.12.008.

[28] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," *Int. J. Life Cycle Assess.,* 2016, doi: 10.1007/s11367-016-1087-8.

[29] M. A. J. Huijbregts *et al.*, "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," *Int. J. Life Cycle Assess.,* vol. 22, no. 2, pp. 138–147, Feb. 2017, doi: 10.1007/s11367-016-1246-y.

[30] R. K. Rosenbaum *et al.*, "USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment," *Int. J. Life Cycle Assess.,* vol. 13, no. 7, pp. 532–546, Nov. 2008, doi: 10.1007/s11367-008-0038-4.