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Life cycle sustainability assessment of a light rail transit system: Integration of environmental, economic, and social impacts

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Abstract

The transition toward sustainable urban transportation has gained importance in recent decades. However, urban transportation has not been addressed for all dimensions of sustainability. This study presents a life cycle sustainability assessment of a light rail transit system in Kayseri, Turkey, by integrating environmental, economic, and social aspects. The sustainability performance of the light rail transit system is evaluated using a cradle-to-grave approach to assess three aspects of sustainability. For the environmental evaluation, a life cycle assessment was applied using SimaPro 8.4.1 PhD version based on ISO 14040 and 14044. The method, which includes nine environmental impact categories, was employed to assess the environmental performance of the light rail transit system with a functional unit of 1 passenger-km. For the economic assessment, life cycle costing was utilized with the functional unit of USD for 1 passenger-km. A social life cycle assessment was applied to assess the social performance of the light rail transit system based on guidelines published by the United Nations Environment Programme in collaboration with the Society of Environmental Toxicology and Chemistry. For the determination of social impacts, 11 subcategories and 18 social indicators were selected. The results showed that the global warming potential and abiotic depletion potential of the light rail system per passenger-km were 2.4E − 02 kg CO_2 eq. and 2.7E − 01 MJ, respectively, with a service life of 50 years. The total life cycle cost of the light rail system was calculated as 0.046 USD for 1 passenger-km. The results also revealed that the main contributor to the total life cycle cost was energy cost, with 92% (2.88E + 08 USD) of the total cost. In the social performance evaluation, it is found that the industry performs well for society, the local community, and workers but has a weaker social performance for the consumer due to a weak feedback mechanism. *Integr Environ Assess Manag* 2021;17:1070–1082. © 2021 SETAC

KEYWORDS: Life cycle assessment, Life cycle cost, Light rail transit system, Social life cycle, Sustainable urban transportation

INTRODUCTION

Currently, the majority of society prefers to live in urban areas for economic, technological, political, and sociological reasons. According to the UN World Urbanization Prospects 2018 report, 30% of the global population lived in cities in 1950; this figure reached 55% in 2018 and is predicted to reach 68% by 2050 (United Nations DoEaSA, 2019). The large population increase in cities in recent decades has a close relationship with the main dimensions of sustainable development: environmental, economic, and social.

With rapid population growth and urbanization, the need for alternative transportation services of societies has increased gradually in recent decades. When economies develop and cities sprawl, the contribution of transport to environmental problems, illness, and death increases sharply worldwide (Sagaris & Arora, 2016). Particularly in large cities, problems related to transport reach high levels due to high energy consumption, environmental pollution, and traffic congestion (Black et al., 2002). Approximately 25% of global energy consumption and CO_2 emissions are related to the transportation sector (Sato et al., 2019). In the transportation sector, road transportation is responsible for 76% of the total global oil consumption, whereas the share of rail transportation is 0.6% (EU, 2016). Thus, policymakers and researchers have made significant efforts to explore low-cost and environment-friendly transportation alternatives to reduce negative environmental impacts and dependence on petroleum fuels.

In recent years, cities have had a greater need for railway systems, particularly for urban and intercity transportation, due to population growth. In particular, cities with a population greater than 1 million will need thousands of kilometers of railway infrastructure and hundreds of railway vehicles within the next few years. Various urban railway transportation modes, such as metros and light

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railway systems, are utilized in some cities because they are more environment-friendly, comfortable, and economically feasible than buses, minibuses, and metro buses.

As several mobility services are developing in urban areas worldwide, the sustainability of mobility services has gained more importance in recent decades. To assess the sustainability of these services by considering three aspects of sustainability—environmental, economic, and social—life cycle-based methodologies have been developed over time (Gompf et al., 2020). Although numerous studies have performed a life cycle assessment (LCA) based on ISO 14040 and ISO 14044, a standardized approach for life cycle costing (LCC) and social life cycle assessment (S-LCA) has not been achieved. However, some examples and guidelines are used for LCC and S-LCA, and the LCC guidelines by Ciroth and Franze (2009) and S-LCA guidelines published by the United Nations Environmental Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) are commonly referenced in the literature (Ciroth & Franze, 2009; UNEP-SETAC, 2009, 2013). In the last decade, the number of studies on determining the environmental impacts of transportation systems has increased gradually, but studies on the economic and social performance of urban light rail transit systems (LRTSs) are limited (Akerman, 2011; Ally & Pryor, 2016; Banar & Ozdemir, 2015; Bilgili et al., 2019; Chang & Kendall, 2011; Chester & Horvath, 2010; Chester et al., 2013; Cooney et al., 2013; Del Pero et al., 2015; Jones et al., 2017; Li et al., 2018; McKenzie & Durango-Cohen, 2012; Ribau et al., 2014; Shinde et al., 2018; von Rozycki et al., 2003). Banar and Ozdemir (2015) compared the high-speed railway (HSR) and conventional railway (CR) systems in Turkey by using LCA and LCC by considering the infrastructure and operation phases. They found that 58% of the total environmental load for HSRs is derived from the infrastructure phase and 42% of the total environmental load is derived from the operation phase. In contrast, they revealed that the main contributor phase for environmental impacts is the operation phase with a 61% share of the total, followed by the infrastructure phase with a 39% share for the CR system (Banar & Ozdemir, 2015). In addition, Shinde et al. (2018) analyzed the environmental impacts of the Mumbai suburban railway in India with the LCA approach. They considered the construction, maintenance, and operation phases of the suburban railway system. Their results indicate that the operation phase has the highest effect on environmental load, with 87%–94% of the total due to electricity consumption generated from nonrenewable sources in India (Shinde et al., 2018). Bilgili et al. (2019) evaluated the various emissions of different transportation scenarios from highway and railway transportation, which has a length of 232 km between two cities, by utilizing LCA. They determined five different scenarios with several ratios of highway and railway transportation for the selected study area. It is found that an increase in railway transportation utilization reduces greenhouse gas emissions. They also revealed that the damage ratio of the ecosystem quality has decreased from 100% to 14.6% when considering that all passengers use railways instead of highways for transportation (Bilgili et al., 2019).

Although there are studies investigating the environmental (LCA) and economic (LCC) performance of railway systems, studies on the S-LCA of railway systems are scarce in the literature. Agaton et al. (2020) investigated the environmental and socioeconomic evaluation of public transport in the Philippines. Their findings highlight the economic advantages of investment for electric vehicles in public transportation with high public acceptance (Agaton et al., 2020). Kennedy (2002) compared public and private transportation systems from environmental, economic, and social aspects for the case of the Greater Toronto Area (GTA). The results of the study showed that public transportation was more sustainable than private transportation from an environmental perspective. It is suggested that the integration of bicycles with public transit and the construction of light rail systems improve the sustainability of GTA (Kennedy, 2002).

Although a few studies related to sustainability assessments of public transportation are available, there are no studies related to life cycle sustainability assessments (LCSAs) of urban railway systems by concurrently integrating LCA, LCC, and S-LCA in the literature. This study aims to present an LCSA for LRTS by integrating environmental, economic, and social aspects with the implementation of LCA, LCC, and S-LCA methodologies for the case of Kayseri, Turkey. To the best of our knowledge, this is the first study of the LRTS, aiming to pave future studies on the sustainability of LRTSs.

Description of LRTS used in the study

LRTS in Kayseri, which started operation in 2008, was evaluated in the study. The system extends over a 34-km route over three corridors, as schematically shown in Figure 1. The LRTS offers service with 68 light rail vehicles, 38 of which are manufactured in Italy and 30 of which are manufactured in Turkey, and there are 55 passenger stations. The LRTS carried more than 36 million passengers in 2016 and 37 million passengers in 2017 (Kayseri Ulaşım, 2021).

METHODOLOGY

The proposed methodology to assess the sustainability of LRTSs is LCSA, which is composed of the integration of LCA, LCC, and S-LCA to cover all aspects of sustainability (environmental, economic, and social) and sustainability.

LCSA

LCSA provides an integrated sustainability evaluation of a product or process by highlighting areas of negative impact for improvements or positive impacts where opportunities can be explored. In the literature, few attempts can be found for LCSA application on several transportation modes by excluding some dimensions of sustainability, as summarized in Table 1. Although several studies have

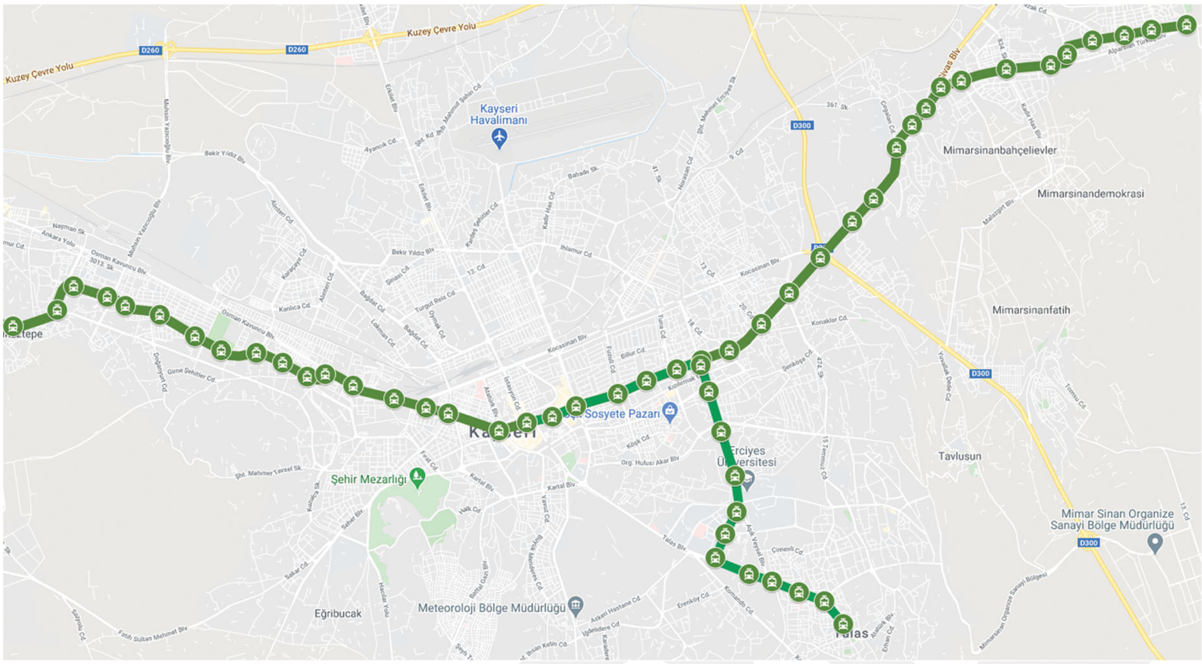

FIGURE 1 Kayseri light rail transit system network (Kayseri Ulaşım, 2021)

addressed LCA and LCC applications for several transportation modes, there is no S-LCA application on transportation systems in the literature (Ally & Pryor, 2016; Banar & Ozdemir, 2015; Chester & Horvath, 2010; Chester et al., 2013; Del Pero et al., 2015; Jones et al., 2017; Li et al., 2018; McKenzie & Durango-Cohen, 2012; Ribau et al., 2014; Shinde et al., 2018; von Rozycki et al., 2003).

Goal and scope. The main goal of this study is to conduct an integrated study of the LRTS regarding sustainability by implementing LCA, LCC, and S-LCA, considering the environmental, economic, and social impacts of the LRTS. According to this goal, the functional unit was chosen as 1 passenger-km rail transportation. The system boundaries of the light rail system considering the cradle-to-grave approach consist of extraction and production of raw materials, transportation of the raw materials to a construction site, vehicle manufacture, transportation of vehicles, construction of the infrastructure, operation, maintenance, and waste disposal, as shown in Figure 2.

LCA

In this study, an LCA was performed based on ISO 14040 and ISO 14044 standards, which cover four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Finkbeiner et al., 2006).

Life cycle inventory. The inventory data for the LRTS were collected from the company that manages and operates the urban light rail system in Kayseri (Tables S1 and S2). The service life of the light rail system was assessed as 50 years. The transport of raw materials to the site is assumed to be 25 km. Data for vehicle manufacturing and transportation of raw materials and vehicles were implemented in the

TABLE 1 Summary of some LCSA application on different transportation modes in literature

	Environmental (LCA)	Economic (LCC)	Social (S-LCA)	References
Light rail	✓	X	X	Chester et al. (2013)
High speed	✓	✓	X	Banar and Ozdemir (2015); Chester and Horvath (2010); Jones et al. (2017); von Royzycki et al. (2003)
Metro	✓	✓	X	Li et al. (2018); Del Pero et al. (2015); Shinde et al. (2018)
Bus	✓	✓	X	Ally and Pryor (2016); Cooney et al. (2013); McKenzie and Durango-Cohen (2012); Ribau et al. (2014)

Abbreviations: LCA, life cycle assessment; LCC, life cycle costing; LCSA, life cycle sustainability assessment; S-LCA, social life cycle assessment.

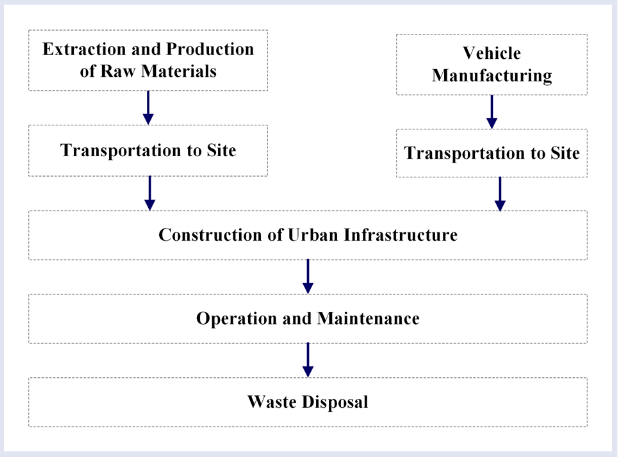

FIGURE 2 The system boundary of the light rail system used in life cycle sustainability assessment

analyses by using the Ecoinvent v3. database, SimaPro 8.4 PhD version.

Life cycle impact assessment. In this study, the CML-IA baseline method was selected for the impact assessment of the LRTSs. The impact categories of this method are listed as follows: abiotic depletion potential (ADP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity (FWAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification potential (AP), and eutrophication potential (EP). For characterization and normalization of the environmental impacts of the light rail system, global and European database values are available in SimaPro software. An ecoinvent database that supplies broader and well-prepared data for many products and processes was utilized for this study (Frischknecht et al., 2005).

LCC

LCC is a financial tool that is widely used to complement LCA analyses for a better understanding of the life cycle evaluation of a product or process from an economic perspective. For the LCC method, there is no specific standard or certification system in the literature; however, various examples and definitions have existed as guidelines (Reich, 2005). In this study, the LCC method was employed in accordance with Ciroth and Franze (2009) using SimaPro 8.4.1 PhD version (Ciroth & Franze, 2009). This LCC method was developed by following the guidelines published in GreenDeltaTC Berlin for this study. Similarly, LCA and LCC analysis should consist of the following stages: goal and scope definition, cost inventory analysis, life cycle cost assessment (LCCA), and interpretation (Simoes et al., 2013).

Life cycle cost inventory. The inventory data for economic assessment of the light rail system were collected from real sectoral sources and the literature (Table S3). These costs were divided into two categories by considering the economic aspects: internal costs and external costs. The calculations were performed considering the functional unit (USD/passenger-km) for internal and external costs. The internal costs were divided into four categories as follows: material costs (concrete, steel, cast iron, aluminum, wood, and glass), energy costs (electricity and diesel oil), transportation costs (transport cost of raw material and vehicles), and disposal costs (landfill and incineration). The external cost components cover only the environmental costs that occur as costs of the impact categories (global warming, acidification, eutrophication, ozone layer depletion, photochemical oxidation, ecotoxicity, and human toxicity) in this study. The cost components of the light rail system were determined by considering the cradle-to-grave approach. The inventory data for the external cost were collected from the literature (Table S4).

LCCA. For the LCCA, the LCC method was created by following the guidelines published by Ciroth and Franze (2009) by utilizing SimaPro 8.4.1 PhD version (Ciroth & Franze, 2009). The method mainly consists of three steps: developing an LCC method, inserting economic issues in processes, and calculating life cycle costs. Characterization, damage assessment, normalization, and weighing properties were determined while creating the new LCC method. Each related cost was then added for each process in the economic issues section per reference unit. After the life cycle with economic values was modeled, SimaPro was employed.

S-LCA

S-LCA is a tool to evaluate the social aspects of a product or process and their actual and potential impacts on social behavior, human welfare, and cultural heritage for all of its stakeholders during the life cycle of the produce or process (Benoît-Norris, 2012). Although there is no specific standardization for S-LCA, the guidelines published by the UNEP in collaboration with the SETAC were followed in the S-LCA section of the study (UNEP-SETAC, 2009, 2013).

Life cycle social inventory. In this phase, it is important to determine the stakeholders affected throughout the life cycle of the light rail transportation system that was being analyzed. Identification of the affected stakeholder categories and subcategories was based on the guidelines published by UNEP-SETAC (UNEP-SETAC, 2013). In this study, four stakeholder categories—workers, consumers, society, and local communities—were identified as four social groups. For the determination of social impacts, 11 subcategories and 18 social indicators were considered, as shown in Table 2.

Based on the identified categories and subcategories, inventory data were gathered from industry reports, site observations, and questionnaires. An online questionnaire was also conducted, which consists of "yes" or "no" type descriptive questions for data collection (Table S5).

TABLE 2 Selected stakeholders, subcategories, and indicators

Stakeholder	Subcategory	Indicator
Worker	Health and safety	Usage of personal protective equipment
		Presence of a formal policy concerning health and safety
		Presence of night work
	Fair salary	Regular payment of the salary
		Employees receiving less than minimum wages
	Working hours	Legal working hours limit
	Child labor	Child labor
Consumer	Health and safety	Organizations' efforts and measures to protect consumer health and safety
		Presence of management measures to assess consumer health and safety
	Feedback mechanism	Presence of a mechanism for customers to provide feedback
		Management measures to improve feedback mechanisms
	Transparency	Consumer complaints regarding transparency
		Publication of a sustainability report
Local community	Local employment	Workforce hired locally
		Local suppliers
	Access to immaterial resources	Presence/strength of community education initiatives
Society	Technology and development	Investments in technology development
	Public commitment to sustainability issues	Presence of publicly available documents as promises or agreements on sustainability issues

TABLE 3 The scoring system for the evaluation of social performance

Subcategory	Percentage	Marks
Cultural heritage	0–20	0
Access to material resources	21–40	1
Safe and healthy living conditions	41–60	2
Health and safety	61–80	3
Feedback mechanism	81–100	4
Privacy, transparency		
Equal opportunities/discrimination		
Public commitment to sustainability issues		
Contribution to economic development		
Technology development		
Transparency	0–20	4
	21–40	3
	41–60	2
	61–80	1
	81–100	0

There was a checklist of 10 questions, and 42 consumers were asked to complete the online questionnaire. The collected data were considered adequate to obtain necessary social data for implementing the S-LCA. All information gathered by questionnaires was cross-checked to compile reliable and consistent inventory data.

Social impact assessment. This phase describes the social and socioeconomic impacts with the calculation of subcategory indicator results, which is referred to as characterization or scoring (UNEP-SETAC, 2009). In this study, a methodology for aggregating the inventory results based on a scoring system was utilized to evaluate the social performance of the LRTS in accordance with the selected subcategories and indicators. First, inventory results gathered from questionnaires were converted into percentages, and then scores were assigned to indicators and subcategories. The percentages obtained from the results of questionnaires were classified into five categories, namely, 0%–20%, 21%–40%, 41%–60%, 61%–80%, and 81%–100%. A score ranging from 0 to 4 is assigned to each subcategory, as indicated in Table 3. Similarly, for subcategories that have more than one indicator, marking ranges from 0 to 4 were also used for each indicator. In this case, the total marks collected for a subcategory will be the average marks of the number of indicators (Foolmaun &

Ramjeeawon, 2013). It is assumed that all indicators and subcategories carry equal weight, and thus the value of each of their weighting factors is one.

RESULTS AND DISCUSSION

LCA results

The environmental impacts of the LRTS for 1 passenger-km rail transportation by considering the cradle-grave approach were calculated with the CML-IA baseline method; the results are presented in Table 4. The LCA analysis consists of nine environmental impact categories (ADP, GWP, ODP, HTP, FWAE, TE, PO, AP, and EP) to reveal the environmental performance of the light rail system. The value of the ADP was calculated as 2.7E – 01 MJ for the LRTS, as shown in Table 4. The main contributor process for ADP was operation and maintenance, accounting for 53% of the total (1.4E – 01 MJ), followed by waste disposal, accounting for 16% (4.3E – 02 MJ). Similar to ADP, operation and maintenance had the highest impact on GWP at 49% (1.2E – 02 kg CO_2 eq.), and the total value of GWP was calculated as 2.4E – 02 kg CO_2 eq. In addition to ADP and GWP, LRTS had high impact categories of HTP and FWAE. The value of HTP was 8.0E – 03 kg 1,4-DB eq., and the value of FWAE was 8.3E – 03 kg 1,4-DB eq. for the LRTS per passenger-km (Table 4).

In environmental performance evaluation, process-based evaluation is critical to show the effects of processes in terms of environmental impacts and to interpret the results in a systematic way. It is also important for decision makers to decide on proper and sustainable new projects and improve existing urban transportation systems by considering process-based sustainability assessments. The distribution of the environmental impact results on the process base (extraction and production of raw materials, transportation of raw materials, vehicle manufacture, transportation of vehicles, operation and maintenance, and waste disposal) for the LRTS is given in Figure 3. Operation and maintenance were the main contributors within the processes considered in the life cycle of the light rail system for the ADP, GWP, HTP, FWAE, acidification, and eutrophication impact categories. The operation and maintenance phase had the highest impacts on FWAE and eutrophication at 67%, followed by acidification and ADP (53%), HTP (50%), and GWP (49.0%). The main reason for these results is the high electricity consumption from fossil-based sources during operation and maintenance and the long period (50 years) of operation. In Turkey, the GWP of electricity production from fossil-based sources (hard coal, lignite, and natural gas) varies between 499 and 1126 g CO_2 eq./kWh, while renewable sources (hydropower, wind, solar, and geothermal) range from 4.1 to 63 g CO_2 eq./kWh. Among all alternative energy sources, hard coal has the highest GWP impact (1126 g CO_2 eq./kWh) and second-highest ADP impact with 13.5 MJ/kWh, following lignite with 15.1 MJ/kWh (Atilgan & Azapagic, 2016). Thus, the high share of fossil fuels in the Turkish national electricity mix and increasing demand due to population growth cause greenhouse gas emissions and other environmental impacts. Shinde et al. (2018) performed an LCA study of the Mumbai suburban railway to assess its environmental performance. Similarly, in this study, they reported that the operation phase is the main contributor, with 87%–94% of the total environmental impact due to the production of electricity from nonrenewable sources in India. In the same study, the second major contributor was the construction phase, which accounted for 24%–57% of the total environmental impact due to material- and energy-intensive rail usage (Shinde et al., 2018). A similar study was performed on a heavy metro train in Rome; the findings revealed that 41%–90% of the total environmental impacts (for 11 environmental impacts) were caused by the operation stage, which is the most influenced stage among the four main stages of material acquisition, manufacturing, operation, and end of life (Del Pero et al., 2015). In addition, Li et al. (2018) quantified the life cycle greenhouse gas emissions of Shangai Metro. They calculated the total life cycle greenhouse gas emissions per the construction length of Shangai Metro as 109,642.81 tCO_2e with a service life of 50 years. Emissions from the operation phase account for 92.1% of the total annual greenhouse gas emissions, followed by material production at 4.1% and the maintenance phase at 3.4% within its life cycle (Li et al., 2018).

In the transportation sector, the GWP is a significant environmental parameter. In this study, the GWP of the light rail system was calculated as 2.4E – 02 kg CO_2 eq. (Table 4). The operation and maintenance process (50%) has the highest impact on the GWP of the light rail system, as shown in Figure 3. Waste disposal (16.6%), extraction and production of raw materials (16.3%), and transportation of raw materials (16.3%) also have an important role in GWP due to greenhouse gas emissions generated from the production of electricity from fossil-based sources. The production of raw materials (especially concrete and steel) and transportation of these raw materials due to fossil fuel consumption contribute to GWP. Similarly, Banar and Ozdemir (2015) found that the GWP of the HSR system is 2.2E – 02 and 2.5E – 02 kg CO_2 eq. for the CR system per passenger-km. They also concluded that the operation of train vehicles has a higher impact on the environmental performance of the HSR and CR system than the infrastructure process (Banar & Ozdemir, 2015). Moreover, Tsai (2017) implemented carbon footprinting on HSRs in Taiwan and determined that the carbon footprint of Taiwan's high-speed rail corporation was found to be 3.8E – 02 kg CO_2 eq. per person-km (Tsai, 2017). The value of HTP was 8.0E – 03 kg 1,4-DB eq. for the light rail system, as indicated in Table 4. Similar to GWP, the main contributor phase for HTP was operation and maintenance with a 50% share of the total impact, followed by waste disposal with a 17.5% contribution (1.4E – 03 kg 1,4-DB eq.). This impact results from materials and fuels used in the operation phase, for instance, diesel oil used in the operational phase of vehicles.

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TABLE 4 Impact category values of LRTS per passenger-km (CML-IA baseline method)

Impact category	Unit	Total	Extraction and production of raw materials	Vehicle manufacturing	Transportation of vehicles	Transportation of raw materials	Operation and maintenance	Waste disposal
Abiotic depletion potential	MJ	2.7E – 01	4.2E – 02	1.0E – 03	3.0E – 05	4.2E – 02	1.4E – 01	4.3E – 02
Global warming potential	kg CO_2 eq.	2.4E – 02	3.9E – 03	9.3E – 05	2.7E – 06	3.9E – 03	1.2E – 02	4.0E – 03
Ozone layer depletion potential	kg CFC-11 eq.	1.4E – 09	3.9E – 10	1.5E – 11	4.2E – 13	3.9E – 10	2.4E – 10	4.0E – 10
Human toxicity potential	kg 1,4-DB eq.	8.0E – 03	1.1E – 03	2.9E – 04	8.3E – 06	1.1E – 03	4.0E – 03	1.4E – 03
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	8.3E – 03	8.1E – 04	1.4E – 04	4.1E – 06	8.1E – 04	5.6E – 03	9.5E – 04
Terrestrial ecotoxicity	kg 1,4-DB eq.	8.2E – 05	1.9E – 05	7.3E – 07	2.1E – 08	1.9E – 05	2.5E – 05	1.9E – 05
Photochemical oxidation	kg C_2H_4 eq.	1.5E – 05	4.1E – 06	5.7E – 08	1.7E – 09	4.1E – 06	2.6E – 06	4.2E – 06
Acidification potential	kg SO_2 eq.	1.2E – 04	1.8E – 05	1.0E – 06	2.9E – 08	1.8E – 05	6.5E – 05	1.9E – 05
Eutrophication potential	kg PO_4 eq.	5.2E – 05	5.3E – 06	5.4E – 07	1.6E – 08	5.3E – 06	3.5E – 05	5.9E – 06

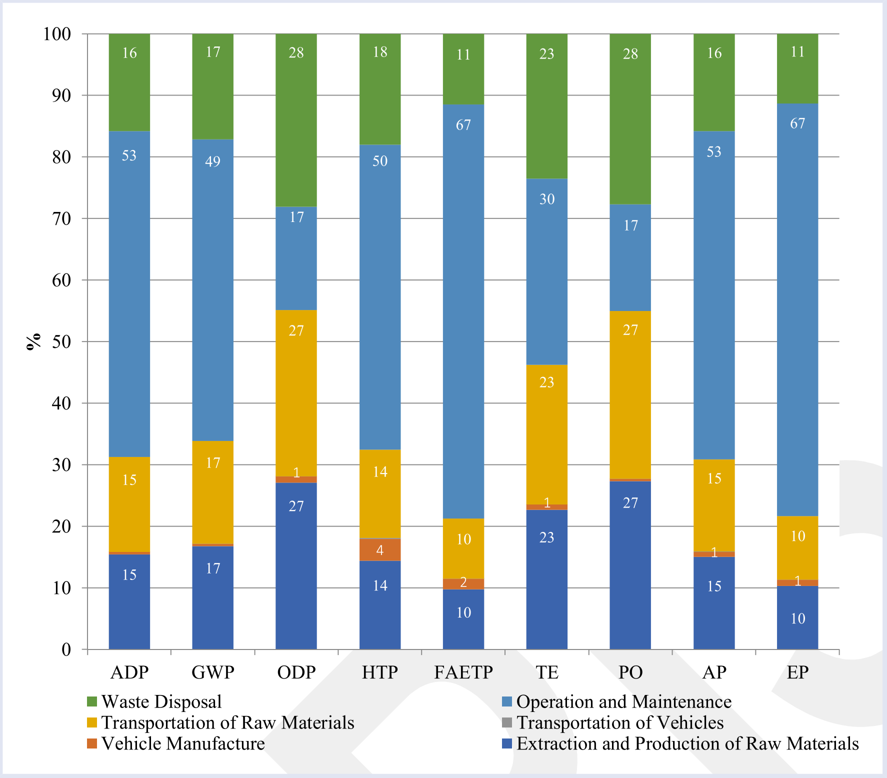

FIGURE 3 The environmental impacts of light rail system based on CML-IA baseline method: CML-IA baseline V3.04/EU25/characterization. ADP, abiotic depletion potential; AP, acidification potential; EP, eutrophication potential; FAETP, freshwater aquatic ecotoxicity potential; GWP, global warming potential; HTP, human toxicity potential; ODP, ozone layer depletion; PO, photochemical oxidation; TE, terrestrial ecotoxicity

LCC results

The results of the cost assessment for the LRTS were calculated using the LCC method, as shown in Table 5. The total life cycle cost of the light rail system was calculated as 3.13E + 08 and 0.046 USD per passenger-km. The main contributor to the total life cycle cost was the energy cost, with 92% (2.88E + 08 USD) of the total cost due to the high consumption of electricity for the operation of the light rail system. The main reason for this finding is the high price of electricity in Turkey and high electricity consumption in the operational phase. Although electricity prices in Turkey (USD 0.09 per kWh) are lower than those in the United States (USD 0.15 per kWh), they are more expensive than those in China (USD 0.08 per kWh) and Russia (EUR 0.06 per kWh) in 2020 (Statista, 2021). As a developing country, the electricity market in Turkey is dominated by fossil fuel technologies. Although renewable energy technologies for electricity production have increased in the total installed capacity in recent decades, in 2019, nearly 60% of the overall electricity was supplied from fossil-based plants, 22% of the overall electricity was supplied from hydropower plants, and a share of other renewables (i.e., solar and wind) was almost 11% (EPDK, 2019). In the Turkish power system, natural gas has a significant share, and supply disruptions from import countries (i.e., Russia and Iran) have caused problems in past winter seasons when energy demand was high. Thus, foreign-source dependence and system contingencies are the main major factors affecting electricity prices in Turkey (Gayretli et al., 2019). In addition, the material cost had the second-highest share, with 8% (2.51E + 07 USD) of the total life cycle cost, as indicated in Table 5. The total life cycle cost of the LRTS per passenger-km was calculated as 0.046 USD.

TABLE 5 The cost values of the light rail system (LCC method)

Cost categories	Total cost (USD)	Unit cost (USD/ passenger-km)
Internal		
Material cost	2.51E + 07	3.69E − 03
Transportation cost	4.36E + 03	6.42E − 07
Energy cost	2.88E + 08	4.23E − 02
Disposal cost	6.24E + 01	9.18E − 09
External		
Environmental cost	1.02E + 04	1.5E − 06
Total cost	3.13E + 08	4.60E − 02

Abbreviation: LCC, life cycle costing.

To the best of the authors' knowledge, in this study, LCC of an LRTS has been performed for the first time; hence, it is not possible to compare the findings of this study with previous findings. However, a study published by Banar and Ozdemir (2015) provides findings for HSR and CR systems in Turkey by using LCA and LCC methods. They compared the

HSR and CR systems by considering the cradle-to-grave approach. Their results show that the total life cycle cost of the HSR per passenger-km is €0.042, and 72% of the total life cycle cost is attributed to the railway infrastructure components. In addition, the total life cycle cost of the CR per passenger-km is €0.037, and 80% of the total life cycle cost is attributed to rail operation (Banar & Ozdemir, 2015). Numerous studies have considered LCCs of several transportation modes, such as high-speed and CR systems; however, LCC studies for LRTSs are scarce in the literature. Thus, this study aims to contribute its findings to the literature and paves the way for further studies.

S-LCA results

The objective of the implementation of the S-LCA was to assess the social performance of the LRTS for four selected social stakeholders. The results of the S-LCA subcategories with the scoring method are presented in Table 6. The inventory results confirmed that there was no case of child labor and forced labor, and that all workers enjoyed social benefits. In addition, all workers received regular payment of their salaries, which is not less than the minimum wage. In addition, working hours were within the legal limits for all workers. Thus, the subcategories of fair salary, working hours, and child labor scored the highest points for stakeholders of workers (Table 6). However, the subcategory of health and safety for workers had a lower score than other subcategories due to the presence of night work for technicians. As indicated in Table 6, night work adversely affects the social performance of the industry despite the workers' use of personal protective equipment and the presence of a formal policy concerning health and safety.

The results of the questionnaires administered to various passenger groups who utilize the LRTS show that the feedback mechanism of the industry received the lowest score for stakeholders of consumers (Table 6). The main reason for administering the questionnaire is to obtain a certain number of responses to weak management measures to improve the feedback mechanism of the industry. Although the industry has a mechanism for consumers to provide feedback, the responses to the questionnaires reveal that management measures are not satisfied for presenting the complaints and suggestions of consumers to the industry. However, the subcategories of health and safety and transparency received a better score than the feedback mechanism. The results of the questionnaires regarding the health and safety of consumers confirmed that the passengers considered that traveling on the LRTS was safe and that they were satisfied with the hygiene of the stations and vehicles. In addition, the transparency subcategory received a score of 3 of 4 due to insufficient information about new projects and developments for passengers.

TABLE 6 The score results of subcategories for each stakeholder

Stakeholder	Subcategory	Score
Worker	Health and safety	3
	Fair salary	4
	Working hours	4
	Child labor	4
Consumer	Health and safety	3
	Feedback mechanism	1
	Transparency	3
Local community	Local employment	3
	Access to immaterial resources	4
Society	Technology and development	4
	Public commitment to sustainability issues	4

The overall results for consumers revealed that the social performance of the LRTS for consumers received the lowest score among all stakeholders. The “society” stakeholder received the highest scores among the five stakeholders for the evaluation of technology and development and public commitment to sustainability issues (Table 6). The industry had a research and development department, which shared their knowledge and experiences with society. The promises or agreements on sustainability issues are published by the industry and are publicly available. Shrivastava and Unnikrishnan (2021) examined the S-LCA crude oil process chain in India and reported that companies need significant improvements to improve their social performance in terms of safety, health, and awareness (Shrivastava & Unnikrishnan, 2021). Lenzo et al. (2017) performed an S-LCA study on the textile industry in Italy by using the subcategory assessment method approach. They considered only two stakeholders (workers and local community); their results showed that only one subcategory (freedom of association and collective bargaining) was marked as “Level C,” which corresponds to 2 (Lenzo et al., 2017). In another S-LCA study, the Thai sugar sector was evaluated by Prasara and Gheewala (2018), who revealed that fair wages, health, and safety, as well as water and land rights, require improvements to enhance social performance. In addition, Liu and Qian (2019) applied an S-LCA of two buildings with different structural frames (prefabricated prefinished volumetric construction [PPVC] and semiprefabrication project) in Singapore by considering the four main stakeholders: workers, occupants of the building, local community, and society. Their results showed that PPVC's social performance is better than semiprefabrication in the subcategories of “health and safety” and “technology development” due to shortened working hours at height and active actions in adopting new construction technology (Liu & Qian, 2019). Moreover, Tsalidis et al. (2020) investigated S-LCA to analyze societal benefits and risks in developing brine treatment systems in the Netherlands, Spain, Poland, and Turkey. They implemented S-LCA in four different case studies of the Zero Brine project by identifying five stakeholders (local community, worker, consumer, value chain actors, and society). All case studies revealed that “labor rights and decent work” and “health and safety” indicators result in the largest impacts due to imports of commodities from developing countries (Tsalidis et al., 2020). Garcia-Sanchez and Guereca (2019) performed S-LCA to assess the working conditions of workers who operate the urban water system in Mexico City based on UNEP/SETAC guidelines. They determined five subcategories: working hours, fair wages, health and safety conditions, social security, and professional development for S-LCA implementation. They employed the scoring scale method for characterization within the range of zero to one and found that the transport stage had the best social performance score, with a value of 0.3 among the water abstraction, water treatment, transport, distribution, use, sewage collection, and wastewater treatment life cycle stages (Garcia-Sanchez & Guereca, 2019).

The urban transportation industry has an important place in society from environmental, economic, and social aspects, as mentioned in the Introduction section. It has been reported that 64% of the total global travel kilometers are attributed to urban areas worldwide (UITP IAoPT, 2014). Although the urban transportation industry has a large share of the global transportation sector, there is a lack of information about its social dimension in the literature. Thus, this study presents for the first time an S-LCA of LRTSs in the literature.

RECOMMENDATIONS

Based on the obtained results, the proposed framework and recommendations for the improvement of each sustainability aspect (environmental, economic, and social), which will guide urban transportation industries in achieving sustainability goals, are provided in Figure 4.

Environmental LCA

For sustainable operation of LRTSs, the usage of solar and wind power generation for electricity instead of fossil fuels can minimize environmental impacts. It is also suggested to use cleaner fuels for transportation. Biofuels, which are more

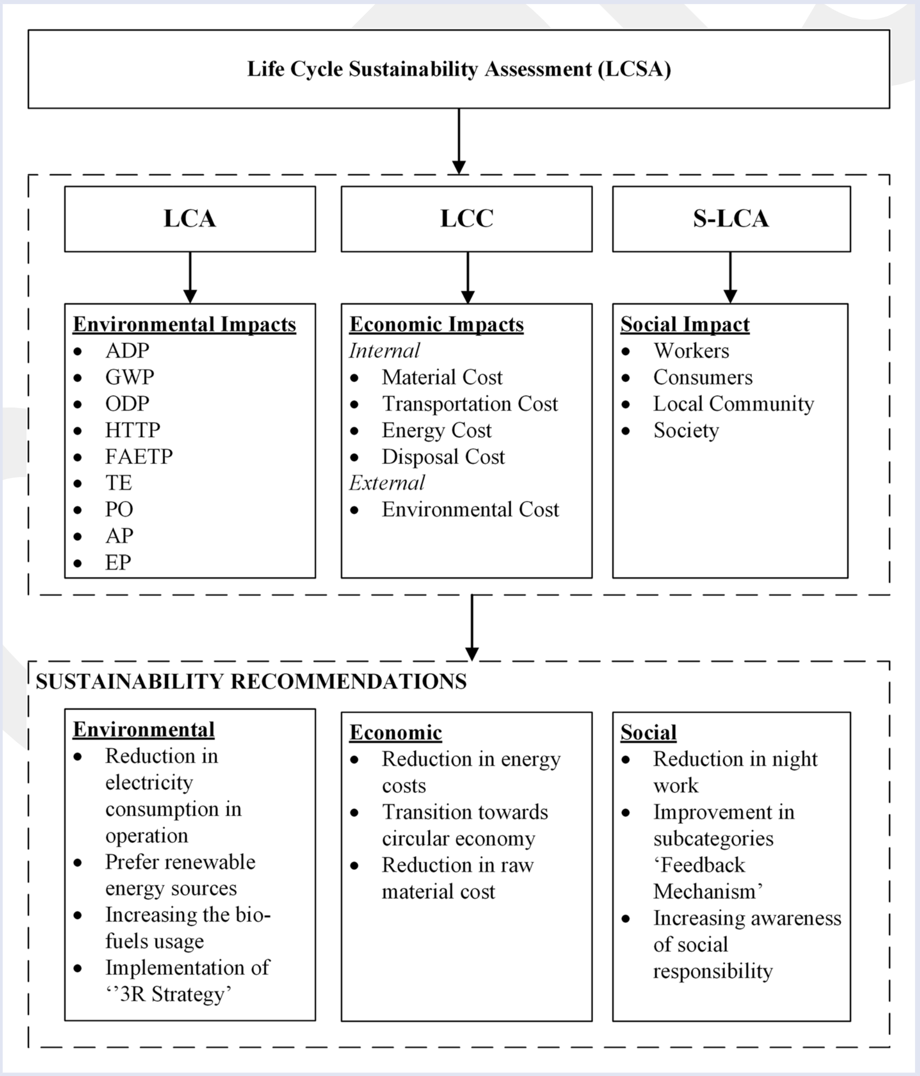

FIGURE 4 Proposed framework for LRTS. ADP, abiotic depletion potential; AP, acidification potential; EP, eutrophication potential; FAETP, freshwater aquatic ecotoxicity potential; GWP, global warming potential; HTP, human toxicity potential; LCA, life cycle assessment; LCC, life cycle costing; LRTS, light rail transit system; ODP, ozone layer depletion; PO, photochemical oxidation; S-LCA, social life cycle assessment; TE, terrestrial ecotoxicity

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environment-friendly than gasoline by providing less GHG emissions, ADP, and OLD, can be utilized as alternative fuels (Balat & Balat, 2009). Apart from this, minimizing material usage by implementing the "3R Strategy," which refers to reducing, reusing, and recycling, can help conserve natural resources with a circular economy approach (Das et al., 2019; Huang et al., 2018). This approach can greatly contribute to reducing the environmental impacts of all transportation systems. Furthermore, durable materials in the construction and operation stages should be preferred to obtaining longer service life, which provides less material and energy consumption. In addition, well optimization of traveling time and frequency with IoT technologies can help save energy, particularly electricity, which is the major problem of transportation systems in terms of environmental performance.

LCC

The overall reduction in the life cycle cost can be achieved by a decrease in the operational cost, particularly a decrease in energy costs. This decrease can be achieved by the integration of utilization from renewable energy resources, such as solar and wind energy. The material cost can be decreased by introducing a circular economy as an alternative to the traditional linear economy, which consists of a make, use, and disposal strategy (Aloini et al., 2020; Geissdoerfer et al., 2018). This strategy can be achieved by implementing the recycling of the maximum amount of raw materials used in the supply chain. Moreover, the transportation cost can be decreased by preferring local suppliers in the supply chain. All recommendations for the environmental LCA mentioned in the previous section can also help to reduce the external costs.

S-LCA

For stakeholder "workers," industries should ensure the adequate health and safety of their workers by providing them personal protective equipment and proper training. Moreover, night work must be reduced or optimized for workers in industries. For "consumers," industries should regularly accept feedback from their consumers and take proper action concerning feedback. However, the COVID-19 pandemic has shown the importance of hand hygiene in public areas. Universal access to hand hygiene facilities in all public areas and transport hubs is recommended by the World Health Organization (WHO, 2020). Thus, hygiene of all areas used by consumers must be provided and controlled periodically within the entire service life. The news and developments related to consumers must be transparent for all consumers to access publicly. For stakeholders of "society," industries must create innovative knowledge and products with investment in technology development and share them with the public. In addition, documents regarding "sustainability issues" must be publicly available to ensure public commitment.

CONCLUSIONS

The integration of three aspects of sustainability for the urban transportation sector is crucial to enhance the sustainability performance of the transportation industry. In this study, the stages with the highest environmental impact, life cycle cost, and social impact are identified by performing an LCSA. Within the scope of LCSA implementation, the environmental, economic, and social performance of a light rail system has been assessed with a holistic approach by using LCA, LCC, and S-LCA.

The results showed that the majority of emissions originated from the operation and maintenance phases of the light rail system, which corresponds to the highest impact with a 50% contribution of the total. These results are mainly due to electricity consumption, which is mostly dependent on fossil-based sources. In the comparison of several cost categories of the entire light rail system, it was found that energy costs are the main contributor (92%); they should be reduced to lower the overall life cycle cost. The social impact assessment showed that urban transportation industries have established a strong relationship with consumers, workers, the local community, and society. However, social performance for the consumer has the lowest score among the four stakeholders. Thus, improvements in the feedback mechanism, health and safety, and transparency are needed to improve the social performance of the LRTS.

Numerous studies have considered the LCA and LCC of several transportation modes, such as metro, high-speed, and conventional light rail systems; however, the integration of LCA, LCC, and S-LCA studies is scarce. Although an evaluation of light rail systems by the LCSA approach is lacking in the literature, this study aims to fill this gap and paves the way for further studies. As a suggestion for future studies, alternative urban transportation scenarios can be assessed with a multicriteria decision-making approach. In addition, several urban transportation modes can be compared in terms of sustainability assessment in further studies.

However, there are some limitations in the study, including the nonavailability of data for environmental LCA and LCC, the long time needed to collect inventory data, and a few social subcategories and stakeholders. Although primary data were mainly employed for LCA and LCC, secondary data were also obtained from the Ecoinvent database, sectoral reports, and journal papers, where the primary data were not present. Another limitation was that the scope of the S-LCA was limited to an urban transportation company, and sufficient databases for an S-LCA that includes all supply chains were not available. Therefore, some stakeholders, such as value chain actors and their subcategories, were excluded from this study. In the literature, the S-LCA method has been shown to be limited when compared with LCA and LCC, and there is no standardized approach. For this reason, while this study makes significant contributions to the novel field of S-LCA and LCSA, it paves the way for further studies in terms of method, database, and analysis.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

The data used in the manuscript are included in the Supporting Information file. Additional data are available upon request from corresponding author Nigmet Uzal (nimetuzal@gmail.com).

SUPPORTING INFORMATION

TABLE S1. Amount of raw materials used during the project.

TABLE S2. Energy consumption during operation.

TABLE S3. Inputs for LCC.

TABLE S4. The quantities of external costs.

TABLE S5. Questionnaire for social life cycle assessment (S-LCA).

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REFERENCES

Agaton, C. B., Collera, A. A., & Guno, C. S. (2020). Socio-economic and environmental analyses of sustainable public transport in the Philippines. *Sustainability-Basel*, *12*(11), 4720.

Akerman, J. (2011). The role of high-speed rail in mitigating climate change—The Swedish case Europabanan from a life cycle perspective. *Transportation Research Part D: Transport and Environment* *16*(3), 208–217.

Ally, J., & Pryor, T. (2016). Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study. *Energy Policy*, *94*, 285–294.

Aloini, D., Dulmin, R., Mininno, V., Stefanini, A., & Zerbino, P. (2020). Driving the transition to a circular economic model: A systematic review on drivers and critical success factors in circular economy. *Sustainability-Basel*, *12*(24), 10672.

Atilgan, B., & Azapagic, A. (2016). An integrated life cycle sustainability assessment of electricity generation in Turkey. *Energy Policy*, *93*, 168–186.

Balat, M., & Balat, H. (2009). Recent trends in global production and utilization of bio-ethanol fuel. *Applied Energy*, *86*(11), 2273–2282.

Banar, M., & Ozdemir, A. (2015). An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods. *Transportation Research Part D: Transport and Environment* *41*, 88–105.

Benoît-Norris, C. (2012). Social life cycle assessment: A technique providing a new wealth of information to inform sustainability-related decision-making. In M. A. Curran (Ed.), *Life cycle assessment handbook: A guide for environmentally sustainable products*. 2012 Scrivener Publishing LLC. pp. 433–452.

Bilgili, L., Kuzu, S. L., Cetinkaya, A. Y., & Kumar, P. (2019). Evaluation of railway versus highway emissions using LCA approach between the two cities of middle Anatolia. *Sustainable Cities and Society*, *49*, 101635.

Black, J. A., Paez, A., & Suthanaya, P. A. (2002). Sustainable urban transportation: Performance indicators and some analytical approaches. *Journal of Urban Planning and Development*, *128*(4), 184–209.

Chang, B., & Kendall, A. (2011). Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system. *Transportation Research Part D: Transport and Environment* *16*(6), 429–434.

Chester, M., & Horvath, A. (2010). Life-cycle assessment of high-speed rail: The case of California. *Environmental Research Letters*, *5*(1), 014003.

Chester, M., Pincetl, S., Elizabeth, Z., Eisenstein, W., & Matute, J. (2013). Infrastructure and automobile shifts: Positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. *Environmental Research Letters*, *8*(1), 015041.

Ciroth, A., & Franze, J. (2009). Life cycle costing in simapro. https://pre-sustainability.com/files/2020/09/LCCinSimaPro_english.pdf. Accessed August 15, 2020.

Cooney, G., Hawkins, T. R., & Marriott, J. (2013). Life cycle assessment of diesel and electric public transportation buses. *Journal of Industrial Ecology*, *17*(5), 689–699.

Das, S., Lee, S. H., Kumar, P., Kim, K. H., Lee, S. S., & Bhattacharya, S. S. (2019). Solid waste management: Scope and the challenge of sustainability. *Journal of Cleaner Production*, *228*, 658–678.

Del Pero, F., Delogu, M., Pierini, M., & Bonaffini, D. (2015). Life cycle assessment of a heavy metro train. *Journal of Cleaner Production*, *87*, 787–799.

EPDK. (2019). Elektrik piyasasi sektor raporu.

European Commission (EU). (2016). A European strategy for low-emission mobility. COM (2016) 501.

Finkbeiner, M., Inaba, A., Tan, R. B. H., Christiansen, K., & Kluppel, H. J. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *International Journal of Life Cycle Assessment*, *11*(2), 80–85.

Foolmaun, R. K., & Ramjeeawon, T. (2013). Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius. *International Journal of Life Cycle Assessment*, *18*(1), 155–171.

Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., & Spielmann, M. (2005). The ecoinvent database: Overview and methodological framework. *International Journal of Life Cycle Assessment*, *10*(1), 3–9.

Garcia-Sanchez, M., & Guereca, L. P. (2019). Environmental and social life cycle assessment of urban water systems: The case of Mexico City. *Science of the Total Environment*, *693*, 133464.

Gayretli, G., Yucekaya, A., & Bilge, A. H. (2019). An analysis of price spikes and deviations in the deregulated Turkish power market. *Energy Strategy Reviews*, *26*, 100376.

Geissdoerfer, M., Morioka, S. N., De Carvalho, M. M., & Evans, S. (2018). Business models and supply chains for the circular economy. *Journal of Cleaner Production*, *190*, 712–721.

Gompf, K., Traverso, M., & Hetterich, J. (2020). Towards social life cycle assessment of mobility services: Systematic literature review and the way forward. *International Journal of Life Cycle Assessment*, *25*(10), 1883–1909.

Huang, B. J., Wang, X. Y., Kua, H. W., Geng, Y., Bleischwitz, R., & Ren, J. Z. (2018). Construction and demolition waste management in China through the 3R principle. *Resources, Conservation And Recycling*, *129*, 36–44.

Jones, H., Moura, F., & Domingos, T. (2017). Life cycle assessment of high-speed rail: A case study in Portugal. *International Journal of Life Cycle Assessment*, *22*(3), 410–422.

Kayseri, Ulaşım. (2021). Raylı sistem haritası. https://www.kayseriulasim.com/. Accessed January 10, 2021.

Kennedy, C. A. (2002). A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area. *Transportation*, *29*(4), 459–493.

Lenzo, P., Traverso, M., Salomone, R., & Ioppolo, G. (2017). Social life cycle assessment in the textile sector: An Italian case study. *Sustainability-Basel*, *9*(11), 2092.

Li, Y., He, Q., Luo, X., Zhang, Y. R., & Dong, L. (2018). Calculation of life-cycle greenhouse gas emissions of urban rail transit systems: A case study of Shanghai metro. *Resources, Conservation And Recycling*, *128*, 451–457.

Liu, S. Y., & Qian, S. Z. (2019). Evaluation of social life-cycle performance of buildings: Theoretical framework and impact assessment approach. *Journal of Cleaner Production*, *213*, 792–807.

McKenzie, E. C., & Durango-Cohen, P. L. (2012). Environmental life-cycle assessment of transit buses with alternative fuel technology. *Transportation Research Part D: Transport and Environment 17*(1), 39–47.

Prasara, A. J., & Gheewala, S. H. (2018). Applying social life cycle assessment in the Thai sugar industry: Challenges from the field. *Journal of Cleaner Production*, *172*, 335–346.

Reich, M. C. (2005). Economic assessment of municipal waste management systems—Case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). *Journal of Cleaner Production*, *13*(3), 253–263.

Ribau, J. P., Silva, C. M., & Sousa, J. M. C. (2014). Efficiency, cost and life cycle CO_2 optimization of fuel cell hybrid and plug-in hybrid urban buses. *Applied Energy*, *129*, 320–335.

Sagaris, L., & Arora, A. (2016). Evaluating how cycle-bus integration could contribute to "sustainable" transport. *Research in Transportation Economics*, *59*, 218–227.

Sato, F. E. K., Furubayashi, T., & Nakata, T. (2019). Application of energy and CO_2 reduction assessments for end-of-life vehicles recycling in Japan. *Applied Energy*, *237*, 779–794.

Shinde, A. M., Dikshit, A. K., Singh, R. K., & Campana, P. E. (2018). Life cycle analysis based comprehensive environmental performance evaluation of Mumbai suburban railway, India. *Journal of Cleaner Production*, *188*, 989–1003.

Shrivastava, S., & Unnikrishnan, S. (2021). Life cycle sustainability assessment of crude oil in India. *Journal of Cleaner Production*, *283*, 124654.

Simoes, C. L., Pinto, L. M. C., & Bernardo, C. A. (2013). Environmental and economic assessment of a road safety product made with virgin and recycled HDPE: A comparative study. *Journal of Environmental Management*, *114*, 209–215.

Statista. (2021). Electricity prices worldwide 2020, by select country. https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/

Tsai, W. T. (2017). Implementation status of Taiwan carbon footprint (CFP) system and a case study of the Taiwan high speed rail corporation. *Sustainable Cities and Society*, *35*, 331–335.

Tsalidis, G. A., Gallart, J. J. E., Corbera, J. B., Blanco, F. C., Harris, S., & Korevaar, G. (2020). Social life cycle assessment of brine treatment and recovery technology: A social hotspot and site-specific evaluation. *Sustainable Production and Consumption*, *22*, 77–87.

UITP IAoPT. (2014). The future of urban mobility 2.0.

UNEP-SETAC. (2009). Guidelines for social life cycle assessment of products. United Nations Environment Programme (UNEP) and Society of Environmental and Toxicology and Chemistry (SETAC).

UNEP-SETAC. (2013). The methodology sheets for subcategories in social life cycle assessment (S-LCA). https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf. Accessed August 15, 2020.

United Nations DoEaSA. (2019). World urbanization prospects: The 2018 revision No. 978-92-1-148319-2.

von Rozycki, C., Koeser, H., & Schwarz, H. (2003). Ecology profile of the German high-speed rail passenger transport system, ice. *International Journal of Life Cycle Assessment*, *8*(2), 83–91.

World Health Organization (WHO). (2020). Water, sanitation, hygiene, and waste management for SARS-CoV-2, the virus that causes COVID-19. https://www.who.int/publications/i/item/WHO-2019-nCoV-IPC-WASH-2020.4