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مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center

Commentary

Mapping the Net-Zero Pathways for Sustainable Transport Systems in Saudi Arabia: The Role of Life Cycle Assessment

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March 10, 2024 | KS--2023-CO07

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KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

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Abstract

Net-zero pathways have become a key climate goal that can help promote a carbon-neutral future by balancing anthropogenic greenhouse gas (GHG) emissions with emissions removed from the atmosphere. These pathways provide strategic frameworks and roadmaps for countries to reduce GHG emissions significantly. For instance, the Kingdom of Saudi Arabia's (KSA) transport sector is responsible for more than one-fifth of KSA GHG emissions. Net-zero pathways are highly relevant for frameworks designed to reduce the sector's GHG emissions, as they help set long-term climate goals such as emission reduction strategies, technology selection and innovation and inform policies and regulations. However, a holistic approach is needed to design net-zero pathways that are effective in practice. The circular carbon economy (CCE) framework adopted by KSA supports this holistic approach. Nonetheless, implementing the CCE framework in the transport sector requires identifying GHG emission sources and driving systemic changes via a life cycle assessment (LCA). This manuscript introduces the LCA approach and its interplay with the CCE framework. This study provides a background for further research in the KSA transport sector to map out plausible net-zero pathways for sustainable transport systems in Saudi Arabia.

Introduction

Pursuing net-zero emissions has become a major climate goal; this approach is reinforced by several scientific assessments and policy frameworks. The need for clear directions and commitments toward reaching a balance between anthropogenic greenhouse gas (GHG) emissions and removal (by natural sink or technology) is evident in Article 4.1 of the Paris Agreement (UNFCCC 2016). The article sets the goal of reaching this balance in the second half of the 21st century, thus aligning with net-zero emissions. This goal was further emphasized in the IPCC's 2018 special report on meeting the 1.5°C warming limit, which discusses pathways to net-zero emissions (IPCC 2018). Most recently, the IPCC Sixth Assessment Report indicated that net-zero emissions are critical for climate stabilization (IPCC 2022). Via analyses throughout these seminal reports, achieving net-zero emissions has clearly emerged as a key climate mitigation objective.

If based on wider sustainability considerations, net-zero emissions pathways could present a blueprint for a carbon-neutral future. These pathways are expected to promote informed choices in the regulatory framework, energy and transportation investments, infrastructure development, and deployment of low-carbon technologies. On a global scale, net-zero pathways aim to balance anthropogenic GHG emissions emitted with those removed from the atmosphere in a given period. At the country level, these pathways are intended to balance anthropogenic GHG emissions emitted into the atmosphere with those removed from the atmosphere (through carbon removal strategies) within the country's boundary in a target year.

GHG emissions and mitigation targets are generally categorized according to the contributions of different economic sectors, such as industry, transportation, and residential/commercial sectors. The Kingdom of Saudi Arabia (KSA) recently made significant efforts to address climate change by setting ambitious net-zero 2060 targets (KSA 2021b). The Kingdom's transportation sector, mostly through the combustion of fossil fuels, was responsible for approximately one-fifth of GHG emissions in 2017 (Shannak, Mikayilov, and Dua 2022). The sector's contribution to carbon emissions is influenced by factors such as high car ownership, road mobility, and fossil-based energy sources (Alajmi 2021)Saudi Arabia's greenhouse gas (GHG. In recognition of the sector's contribution to GHG emissions, net-zero emissions pathways for sustainable transportation systems in the Kingdom urgently need to be mapped out.

The sector should strive for nearly zero emissions by first mitigating GHG emissions (through avoidance and reduction) before offsetting to compensate for residual emissions that cannot be mitigated. Therefore, designing net-zero pathways for sustainable transport systems in KSA requires an all-inclusive approach, as the whole supply chain influences the sector's contribution to GHG emissions and climate change. This holistic approach considers, among others, evaluating several mature and emerging technologies, including existing and new policy approaches that cover several crucial dimensions of climate challenges.

KSA has adopted the circular carbon economy (CCE) framework as part of a broader set of plans (such as the Saudi Green Initiative) to achieve net-zero GHG emissions by 2060 (KSA 2021b, 2021a), thus demonstrating its commitment to environmental sustainability. The CCE framework further supports

KSA in merging its domestic interests with efforts to achieve sustainable net-zero emission pathways. This framework, among others, is an important component of the holistic approach required for designing net-zero pathways, as it promotes the inclusion of several technological options to achieve global climate goals. While the circular economy broadly focuses on emissions and material flow, the main goal of the CCE framework is to reach net-zero GHG emissions by both reducing and recycling CO_2 emissions (e.g., through bioenergy), reusing them (e.g., through industrial CO_2 usage), and removing them through capture and storage and direct CO_2 capture from the atmosphere (Shehri et al. 2022; Luomi et al. 2021) Saudi Arabia launched the concept of the circular carbon economy (CCE. The CCE framework further emphasizes the important role of carbon removal strategies and technologies — such as direct air capture (DAC), carbon capture and storage/sequestration (CCS), bioenergy with carbon capture and storage (BECCS), and carbon capture, utilization, and storage (CCUS) — in reaching global climate targets (Bistline and Blanford 2021).

However, the effective implementation of the CCE framework for net-zero pathways in the transport sector is more complex. First, KSA must identify GHG emission sources; then, the necessary systemic changes across relevant sources must be implemented to address them. Therefore, developing and deploying sustainable net-zero pathways for the transport sector depends on the Kingdom's ability to understand the life cycle environmental performance of the various transport systems, including when carbon removal and utilization technologies are used in producing alternative fuels. This implies that broader environmental considerations should be integrated into the design process for sustainable transportation systems in KSA to ensure that carbon emission reduction and removal efforts do not undermine sustainable development efforts.

As a result, approaches that support informed decision-making by quantifying and identifying GHG emission sources (including other environmental impacts) from a life cycle perspective are crucial. One such tool is Life Cycle Assessment (LCA), which is an effective decision-support tool for promoting sustainable mitigation pathways. It compares alternatives and provides a comprehensive view of processes, products, and systems' environmental impacts throughout their lifetime. LCA can be used to identify environmental hotspots and mitigation opportunities, thus guiding decisions toward more sustainable pathways.

Considering the above context, this manuscript introduces the LCA methodology to further research in our programs. Specifically, the study suggests the usefulness of LCA as a quantitative assessment tool to drive and inform CCE considerations in the KSA transport sector. The authors believe that integrating a life cycle perspective in implementing the CCE framework can promote environmental considerations in designing sustainable transitions in the transport sector. Hence, by 2060, KSA will be one step closer to achieving its green initiatives and net-zero aspirations.

Overview of LCA

An LCA is a standardized science-based approach for quantifying the environmental burden of activities, products, processes, services, and systems during every life cycle stage. The life cycle of a product or system extends from material extraction and processing to transportation, production, packaging, use, reuse, recycling, and final disposal of waste at the end of life.

Framing an LCA

Framing an LCA starts with identifying the relevant direct and indirect (including supply chain) processes of the transportation system. Considering that the primary function of the transport system is to move people and goods across places, the direct impacts are energy/fuel consumption and associated emissions with vehicle movement. Indirect impacts are those associated with the vehicle, infrastructure, energy production, and supply chain services.

The LCA can be framed from either a retrospective or prospective standpoint. This aspect is particularly important considering the projected changes toward net-zero pathways in future energy and transport systems. A retrospective LCA uses past data to estimate environmental performance and identify areas for improvement. In contrast, a prospective LCA considers current and future parameters by asking how direct and indirect processes in a transportation system will change based on existing policy implementation.

Retrospective LCAs have dominated vehicle LCA studies until recently, but prospective thinking has taken a more significant role as practitioners use LCA to guide policy and decision-making processes. However, these two approaches can inform environmental impact reductions, and practitioners should choose the most appropriate approach based on the LCA aim. The chosen approach for defining the assessment goal will determine the system boundary for analysis.

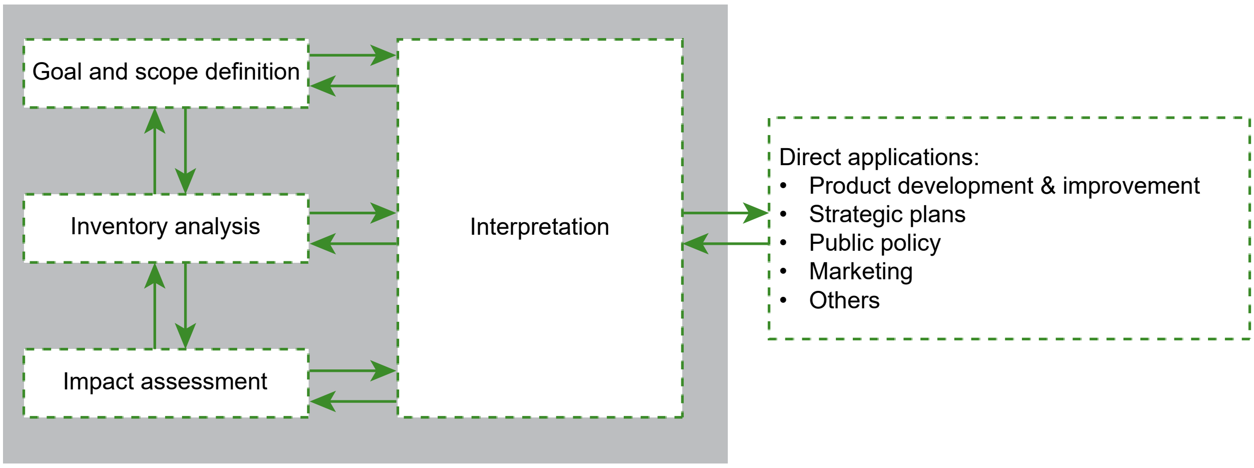
Conducting an LCA

Conducting an LCA generally follows a four-stage approach, as shown in Figure 1—goal and scope definition, inventory analysis, impact assessment, and interpretation. Defining the goal and scope of the LCA study is always the first step. The LCA's why, what, and how are defined at this stage.

Generally, the goal includes the intended application, decision context, and intended audience of the study. Therefore, this stage is the most decisive of all the LCA stages. The scope defines the functional unit and the system boundary, including spatial and temporal limits. The functional unit is the quantified performance of a product or service delivered to its end user. Simply put, it describes the quantity of a product, system, or service based on the performance it delivers to its end user. The functional unit indicates that the LCA is analyzing a product or system function since the function and performance of the product or system under study is considered. As a result, the functional unit in the LCA is used as a reference unit in the LCA model. The level of detail presented at this stage of the LCA strongly depends on the goal and intended application of the study.

The second stage — inventory analysis — prepares life cycle inventories by quantifying the input and output flows (i.e., energy and mass flows) for two key aspects. First, the supply chain activities and processes involved in the life cycle (from raw material extraction to production, use, and end of life) of the product, system, or service under

Figure 1. Life cycle assessment framework (ISO, 2006)



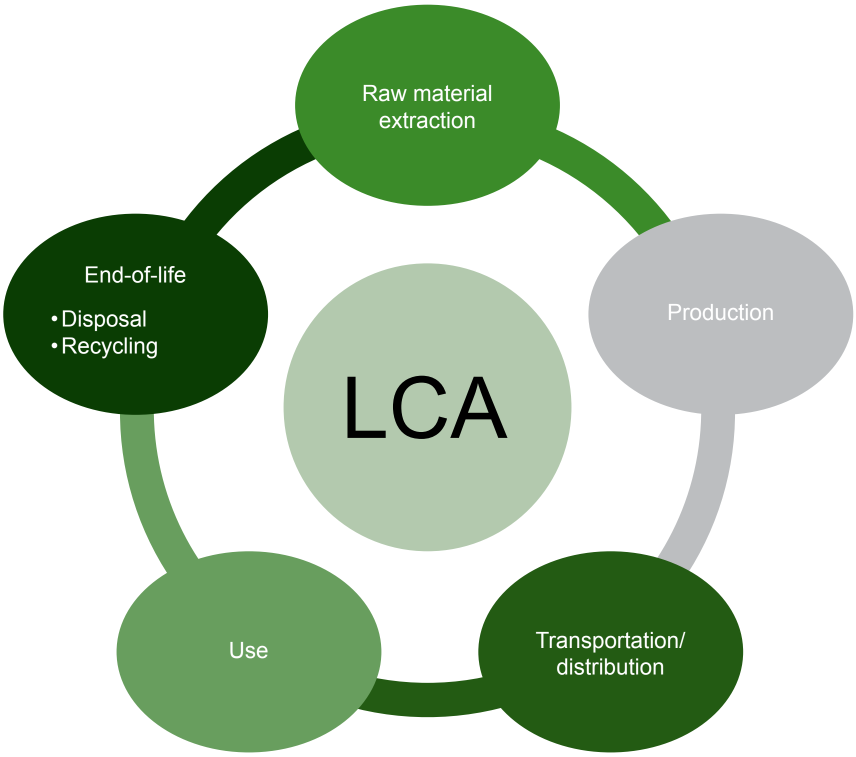
study are defined; second, the approach used to solve multifunctionality issues is chosen. Multifunctionality issues result from the processes or approaches for allocating certain impacts to products, processes, or multiple products/services systems that could be attributed to different functions (often called coproducts) (Schaubroeck et al. 2022). The third stage — impact assessment — estimates the environmental burden associated with the materials and energy flows defined during the inventory analysis stage. Most LCA studies use established life cycle impact assessment (LCIA) methods described in the literature or LCA software to quantify impacts associated with different environmental indicators. LCIA methods quantify the potential environmental burden associated with products, processes, or systems throughout their life cycle. They systematically estimate potential impacts on several environmental categories, such as climate change, air pollution, and resource depletion. The environmental categories covered by the LCIA should be defined during the goal and scope definition to ensure that the data collected during the inventory stage remain relevant to the objectives of the LCA.

The final stage — interpretation — is the evaluation stage. The results achieved are analyzed and interpreted at this stage. LCA practitioners can use the analyzed results to draw conclusions and recommendations for informed decision-making and policymaking. The entire LCA process can be performed iteratively. For instance, choices in one stage can lead the practitioner to visit earlier stages and make relevant changes to match the goal of the assessment. The iterative process in LCA facilitates feedback and learning, allows data and assumption refinements, and enables sensitivity analysis and scenario testing, among others. This iterative process helps improve the accuracy, reliability, and relevance of LCA results to inform the decision-making process.

What sets LCA apart?

The holistic nature of an LCA sets it apart from other environmental assessment tools. LCA considers the entire life cycle of a product, process, or system from raw material extraction to recycling and disposal at the end of life (see Figure 2). This comprehensive approach ensures that all stages and activities linked with the object under assessment are considered, thus providing a more accurate and complete understanding of the object's environmental profile. In addition, burden shifting can be avoided by assessing various environmental categories, identifying hotspots for environmental improvement, and promoting system-wide optimization from a life cycle perspective.

Figure 2. The holistic nature of LCA

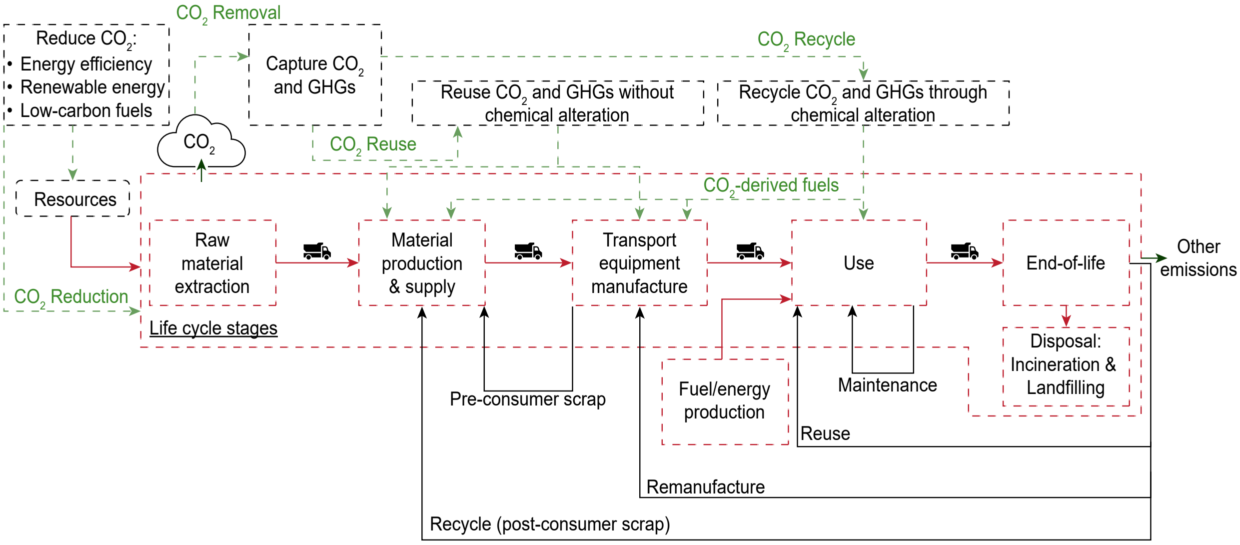


Interplay between LCA and CCE Frameworks

Addressing climate change under the CCE framework necessitates the adoption of strategies aimed at removing CO_2 from the atmosphere in addition to reducing, recycling, and reusing carbon emissions. A key pillar of the CCE framework is transitioning from a linear carbon economy, where CO_2 is seen as a waste, to a CCE, where CO_2 is seen as a resource that can help hard-to-abate sectors meet global climate targets (Hepburn et al. 2019). The interplay between CCE and LCA frameworks for sustainable transportation systems is shown in Figure 3. The traditional application of LCA is shown in red for energy and material flows and via solid black arrows for material circularity, and the circular carbon strategy considerations are shown via green dashed lines for removing, recycling, reusing, and reducing carbon within the CCE framework.

For instance, the CCE framework can include promoting sustainable fuels such as biofuels, hydrogen, or synthetic fuels derived from CCU technologies (Jiang et al. 2010)as our demand for energy inevitably increases, so do emissions of greenhouse gases, most notably carbon dioxide (CO2. These fuels have the potential to decarbonize the transport sector and reduce its contribution to global GHG emissions, as they can be employed during vehicle production and usage — shown as CO_2-derived fuels in Figure 3. In addition, as CCU technologies advance and become cost-effective, mobile carbon capture technologies could be implemented in transport equipment for direct carbon capture from exhaust during usage (Aramco 2020). Similarly, CCE strategies can potentially implement DAC to capture CO_2 emissions from transport equipment manufacturing plants (including manufacturing facilities for materials used in vehicles) and can also be employed in constructing/manufacturing transport infrastructure. For instance, using carbon-utilizing building materials (such as concrete, bricks, and asphalt) in infrastructure projects could reduce the embodied carbon in the construction/manufacturing process.

Figure 3. A schematic representation of the interplay between LCA and the CCE for assessing circular carbon strategies in transport equipment, adapted from (*CCE n.d.*)



However, the engineered processes for managing carbon circularity, shown as green dotted line arrows in Figure 3, do not ensure environmental sustainability alone. Therefore, the environmental performance of carbon circularity strategies and technologies should be quantified and compared to that of their already established counterparts to identify environmental hotspots and avoid pathways that could undermine net-zero efforts. For instance, using CO_2-derived fuels in the transport sector is associated with upstream emissions and should be considered in the LCA of transport systems.

Figure 4. A schematic representation of an LCA informing decision-making and policy in the CCE framework

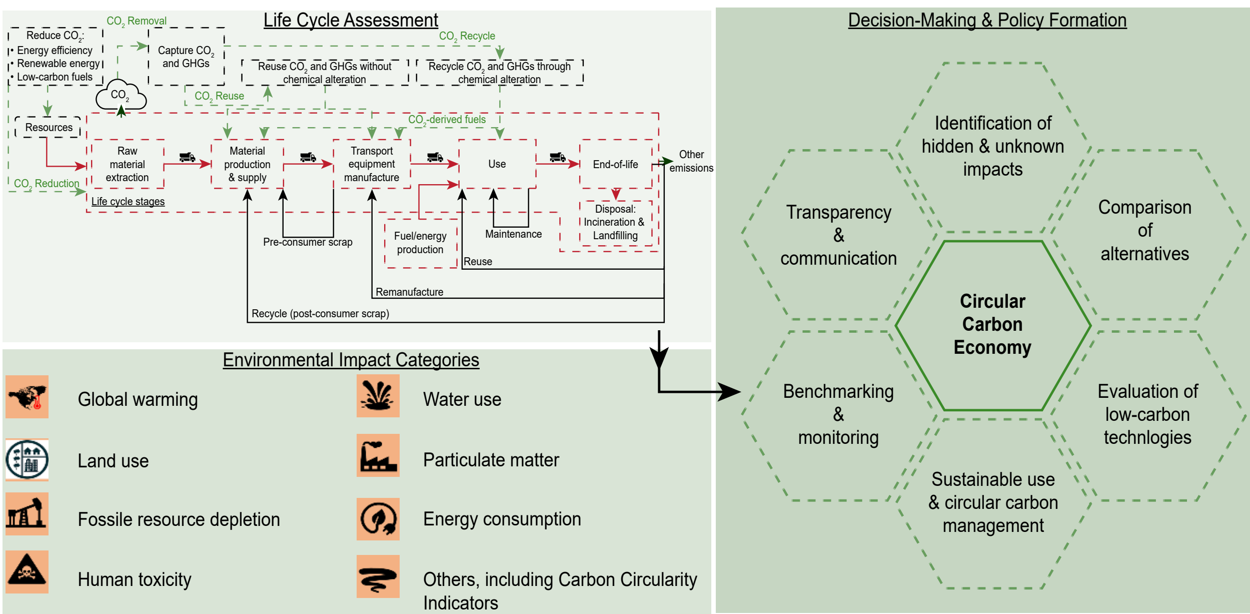


Figure 4 shows a schematic representation of how LCA informs decisions and policymaking in the CCE framework. The blue arrows in the figure show decision and policymaking steps — from conducting an LCA and identifying environmental consequences across several indicators to considerations for decision and policymaking. This approach suggests that integrating LCA into the CCE can provide answers to KSA decision makers when the right questions are asked. For instance, among the existing CO_2 capture and utilization pathways, we can ask which is most sustainable for KSA transport systems under the CCE framework. We can further ask which parameters and economic sectors influence the results most and how the pathways' environmental profiles would change, considering projected future changes in key sectors or parameters. Likewise, when assessing the role of hydrogen in the CCE, LCA can be used to evaluate the environmental profile of alternative production pathways for hydrogen and its derivatives and provide insights into which option is more environmentally friendly.

Overall, LCA can support the implementation of the CCE by identifying emission hotspots and improvement opportunities, evaluating carbon removal technologies and scenarios, benchmarking alternative mature systems, and measuring the effectiveness of CCE strategies. This process helps to ensure that the decisions made within the CCE framework are based on robust scientific assessments and promote the sustainable use of resources, emission reduction, and environmental stewardship.

LCA as a Decision-Support Tool

The net-zero concept significantly emphasizes balancing climatic objectives and broader sustainability considerations, such as environmental preservation, social fairness, economic feasibility, and resilience (IPCC 2022). Thus, decision-support tools are paramount to designing and achieving these pathways since they offer scientific analysis, data, and models that inform the decision-making process (Molina-Perez 2023).

In that light, LCA informs decision-making and policy by providing comprehensive environmental insights, as shown in Figure 4. Its use in decision-making and policy formulation is evident in the literature. For instance, Cox et al. (2020)life cycle environmental burdens and total costs of ownership (TCO and De Clerck et al. (2018) conducted LCA studies to quantify the environmental and societal impacts of different vehicle technologies. Koroma et al. used the LCA methodology to quantify the environmental implications of expected changes in vehicle manufacture, powertrain components, operation, and end-of-life stages (Koroma et al. 2022, 2020, 2023)assessing their environmental performance should consider changes in the electricity sec- tor and refurbishment oftheir batteries. This study conducts a scenario-based Life Cycle Assessment (LCA. Additionally, instances of researchers highlighting the application of LCA for creating a sustainable product and process include a study by Ott et al. (2023) in the food and feed sector and one by Kralisch et al. (2015) in the chemical sector.

Likewise, LCA has been used to support the formulation of various policies and regulations, such as the End-of-Life Vehicle Directive (EU 2000), the Waste Electrical and Electronic Equipment (WEEE) Directive (EU 2003), Zero-Emission Vehicle Mandates, and the Renewable Energy Directive. LCA studies have also played a pivotal role in shaping eco-labeling and environmental product standards (Fet and Skaar 2006).

LCA for transportation decisions and policymaking

Applying LCA in the KSA transportation sector would provide valuable insights toward improving its environmental profile. As the Kingdom's transportation sector significantly contributes to GHG emissions, understanding and mitigating its environmental impacts is crucial for achieving net-zero emissions targets. Therefore, an LCA can provide a systematic approach to assess the life cycle environmental profile of various transportation systems, thus guiding decision-making toward net-zero pathways for sustainable transportation in Saudi Arabia. Additionally, LCA can complement the CCE framework by identifying the derived benefits and unforeseen challenges of implementing it in the transportation sector. For example, using CO_2-derived fuels is not carbon free; it comes with environmental impacts — from manufacturing carbon removal and utilization technologies to the energy consumed during their use and disposal stages, among others (Somoza-Tornos et al. 2021). Therefore, LCA and the CCE are well matched to inform the development and implementation of sustainable net-zero pathways for the transport sector, as they identify and assess various alternative fuels and technologies, GHG emissions, energy consumption, and other environmental indicators. Specifically,

1. LCA can provide insights to further improve our understanding of the full impacts associated with transportation systems. Historically, transportation decision-makers have considered only direct emissions and energy consumption linked to transport infrastructure (facilities) and operations. Arguably, most transportation agencies have overlooked emissions associated with equipment manufacture, conventional fuel refining, alternative fuel production, and end-of-life management. These overlooked emissions (mostly from upstream activities) can significantly influence the life cycle profile of transport systems. As governments worldwide enact policies and net-zero pathways to mitigate climate change and GHG emissions, reducing these emissions in the transport sector is becoming increasingly important. LCA can be used to quantify and identify these “hidden” emissions.

2. Similarly, LCA can provide insights into the environmental profiles of different transportation modes by comparing and benchmarking available technologies. The quantity of energy consumption, including GHG emissions and other pollutants that occur during the operation phase of transport systems, can vary across technologies and modes. For instance, conventional vehicles emit tailpipe emissions during operation, while electric vehicles (EVs) do not; however, upstream emissions are associated with conventional vehicles and EVs (charging electricity). Likewise, variations in the local context can influence the environmental performance of transport and energy systems, especially for emerging technologies. For example, the performance of EV batteries can vary under different operating temperatures, thus influencing their total environmental performance in different local contexts (Wang et al. 2019; Hannan et al. 2020; Yuksel and Michalek 2015)commercial 18650 Li-ion cells with NCA/C chemistry are cycled deeply1000 times at either 25 °C or 60 °C using two different charge termination protocols: (a. Therefore, by considering key parameters, LCA is vital for assessing and comparing the environmental performance of different technologies and modes of transport. This approach will help establish benchmarks and provide a solid base for monitoring sustainable transportation systems.

Challenges and Considerations

Although LCA is considered a valuable tool for estimating the environmental impacts of products or systems across their whole life cycle, its application in transport systems poses unique challenges and considerations. Key difficulties include modeling complex supply chains, allocating environmental impacts across multiproduct processes, and managing large variability in use phase impacts (Del Duce et al. 2013). Transportation LCAs should account for global and multitiered supply chains in equipment manufacturing and energy/fuel production, among others. Allocation methods are crucial for assigning impacts to transportation versus other co-products or processes, such as oil refining, biofuels, and CO_2-derived fuels.

The use of phase variability also complicates modeling impacts across diverse driving conditions, vehicles, fuels, and lifetime mileage levels. Furthermore, transportation LCAs require localized assessments to capture regional differences in temperature, energy/fuel generation, and other background processes. To address these challenges, LCA practitioners should make informed methodological choices regarding system boundaries, data sources, allocation methods, and impact assessments. Thus, conducting rigorous, comprehensive LCA of transportation systems necessitates an understanding of these key complexities and limitations.

- Data availability: Obtaining accurate and comprehensive data for all life cycle stages of transport systems, including vehicle production, operation, and end-of-life disposal, can be challenging. Data gaps and limited access to specific industry data can lead to reliance on generic data, introducing uncertainty.

- System boundaries: Defining appropriate system boundaries for transport systems is complex due to the interconnections between different components and processes. Deciding what to include and exclude in the assessment can impact the outcomes and interpretation of LCA results.

- Data quality: Ensuring the quality and reliability of the data used in an LCA is critical. The data may come from various sources with varying degrees of accuracy and consistency, leading to potential biases and uncertainties in the assessment.

- Variability and uncertainty: Transport systems exhibit variability in terms of vehicle types, fuel sources, usage patterns, and geographical contexts. Incorporating this variability into an LCA can be challenging and may require representative data or scenario analysis to account for different usage scenarios.

- Technological advancements: Rapid advancements in vehicle technologies, alternative fuels, and infrastructure can quickly render LCA results outdated. Keeping pace with technological changes and updating LCA models and data accordingly is necessary for accurate assessments.

Final Remarks

Given the current state of the KSA transportation sector and the challenges associated with decarbonizing it, the transportation sector may be challenged to reach net-zero emissions by 2060. However, significant progress can still be made toward that goal within the proposed timeframe. The application of LCA in the transportation sector can provide valuable insights for improving the environmental profile of transport systems, guiding decision-making toward implementing the CCE framework and defining net-zero pathways in the KSA transport sector. For LCA research at KAPSARC and within the Kingdom, addressing the challenges of LCA evaluation methods for transport systems and considering the need to conduct rigorous and comprehensive LCA studies are crucial. This process includes researching proposals on the LCA of current and emerging transportation technologies, including production pathways for alternative low-carbon fuels and materials. In addition, collaborating with relevant stakeholders, collecting reliable data, developing robust methodologies, and remaining abreast of technological and policy advancements can contribute to positioning KAPSARC in the LCA and environmental research space. By doing so, KAPSARC researchers using the LCA methodology can contribute to advancing LCA evaluation methods for transport systems. As a result, they will contribute to developing and implementing plausible net-zero pathways for the transport sector in Saudi Arabia while supporting the Kingdom’s efforts to mitigate climate change and achieve environmental sustainability.

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About the Project

This work is performed under the “Mapping the Net-Zero Pathways to Sustainable Transport in Saudi Arabia” project. The project aims to create an evidence-based, comprehensive understanding of the different projects, policies, and regulations concerning international connectivity, regional transport, and urban mobility in Saudi Arabia. It considers the contributions of these factors to energy demand and aims to lower GHGs and emissions while setting the Kingdom on a net-zero pathway. KAPSARC is engaged in understanding the role of life cycle assessment in informing sustainable net-zero transportation pathways among other key economic sectors. This commentary manuscript strives to introduce the life cycle assessment in the context of implementing the CCE framework in the transport sector.

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