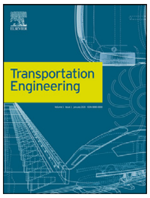
Transportation Engineering 2 (2020) 100019

Contents lists available at ScienceDirect

Transportation Engineering

journal homepage: www.elsevier.com/locate/treng



Life cycle inventory of bitumen in South Africa

Sheldon A. Blaauw[a,b,*], James W. Maina[a], Louis J. Grobler[c]

[a] Department of Civil Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa
[b] Ove Arup & Partners Limited, 1st Floor City Gate West, Tollhouse Hill, Nottingham NG1 5AT, United Kingdom
[c] Dinokeng Engineers, Office@Nature, 500 Botterklapper Street, Die Wilgers, Pretoria 38602, South Africa

ARTICLE INFO

Keywords:
Life cycle assessment
Life cycle inventory
Pavement sustainability
Carbon dioxide equivalent
Bitumen

ABSTRACT

Road pavements are constructed of bulk raw materials such as aggregate, cement, bitumen and water. The environmental, social, and economic impacts of the materials and processes should be quantified and monitored towards the optimisation of pavement design. At present, no such protocol is in place in South Africa. This paper proposes a framework for the development of a pavement life cycle assessment model, starting by documenting the life cycle inventory for bitumen, one of the leading environmental and social burdensome materials used for pavement development.

This inventory acts as the first building block in the development of a life cycle assessment model by evaluating and delineating primary flows (inputs of materials and energy and outputs of pollution) related to the supply chain of bitumen in South Africa. The primary flows are represented by indicators which measure their quantitative impacts. The inventory provides impact category indicators for environmental and social related emissions, energy- and water-use and currently excludes other indicators such as emissions to water, waste generation, jobs creation and economic transformation, amongst others. These indicators are omitted due to lack of quality data at present and difficulty in the quantification of impacts, but recognition is given to their relevancy and importance.

The approach is envisioned to function as the first version of a living protocol that will be improved on through further research. Although the primary target audience is South African road authorities, the approach can be adapted for use in any country.

1. Introduction

Road pavements are constructed of bulk raw materials such as aggregate, cement, bitumen and water. The environmental, social, and economic impacts of the materials and processes should be quantified and monitored towards the optimisation of the pavement design. At present, no such protocol is in place in South Africa. The need was identified to develop a holistic life cycle assessment (LCA) model of the effects of alternative pavement designs and technologies in terms of construction, maintenance and rehabilitation. A life cycle inventory (LCI) is the first step in the development of an LCA.

The LCI analysis phase consists of the tracking of flows (inputs of materials, resources and energy and outputs of waste, pollution and co-products) which are represented by indicators for the system being studied [1]. For a typical asphalt plant, the indicators are listed in the inventory in terms of energy use, the use of materials such as aggregates, bitumen and water and the production of greenhouse gasses. These are referred to as the primary data sources for an LCI, which are to be traced back to their origin, known as the background data processes [1]. For bitumen, the background processes involve extraction processes whereas for energy, they may include delivering the crude oil to the place of refining. Due to the influence of background processes, it is important to develop inputs to an LCI regionally and consider the typical practices and available resources of that region. It is often challenging collecting data from regions which do not voluntarily publish data regarding the processes or resources used to produce pavement materials. In these situations, published data sets (either commercial sources or from literature) are often utilised. The issues related to the use of proxy data were observed in the early years of pavement LCI development [2] when studies were rapidly published and had numerous flaws. These flaws commonly manifested as poor-quality data, gaps in research being filled by proxy data and a general lack of consideration for location specific evaluations.

Certain inventories are often viewed as ‘golden black boxes’ [3] and applied without much appreciation for inherent limitations in the inventories. Considering the widely cited Eurobitume inventory, originally published in 2012 [4] and revised in 2020 [5]. The inventory has varying embodied carbon factors applied to certain elements of the inventory

---

[*] Corresponding author.
E-mail address: sheldon.blaauw@arup.com (S.A. Blaauw).

https://doi.org/10.1016/j.treng.2020.100019
Received 14 July 2020; Received in revised form 1 September 2020; Accepted 1 September 2020

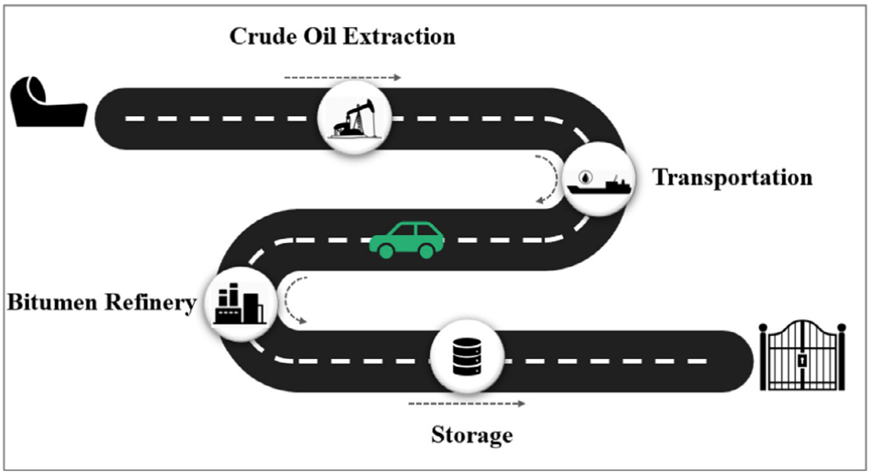


Fig. 1. System boundaries of the assessed system.

between the two data sets, with up to 50% differences in some instances. This highlights the impacts of lack of quality data on predictions. An additional flaw present in LCI development models is the inconsistency in selecting impact categories; where energy and carbon emissions are typically focused on with other important indicators such as water use often being omitted [6]. Focus on a holistic inventory which incorporates both environmental and social indicators, as demonstrated by Bressi et al. [7], is required.

Supporting the need to quantify these indicators, Giunta et al. [8] demonstrates the contributions of various pavement life cycle phases (excluding the use phase) to the total energy and carbon footprint estimates for a typical pavement project. Giunta et al. found that the production phase generally accounted for more than 50% of the total energy and emissions related to pavement development, with bitumen production being the leading material contributor. Methods, such as the use of recycled polystyrene to substitute bitumen, are available to reduce these impacts [9].

The inventory detailed in this study is specific to South Africa but can be modified to be representative of any country. This approach follows the notion that sustainability is spatially dependant and influenced by local boundaries [10]. The research highlights the typical processes bitumen undergoes during production and the common constraints experienced in the development of an inventory for penetration-grade bitumen. Furthermore, the need to develop country specific inventories is demonstrated through data validation and sensitivity analyses, to highlight key factors affecting estimates and support conclusions and recommendations.

2. Method: life cycle inventory

2.1. Goal and scope

The goal of this study is to provide an inventory for the production of straight-run penetration grade bitumen in South Africa. International Organisation for Standardisation (ISO) standard 14040 [11] was used to develop this inventory. The inventory is intended to act as a building block on which to improve and develop further life cycle inventories where penetration grade bitumen is used with the ensuing intention to develop a holistic LCA model for pavement infrastructure in South Africa.

The scope of the study extends from cradle-to-gate for the production of penetration grade bitumen at any refinery in South Africa. The inventory provides indicators for environmental and social related emissions, energy- and water-use but currently excludes other indicators such as emissions to water and waste generation. Social related indicators including jobs creation, local economic development, and economic transformation are also excluded from consideration. These indicators are omitted due to lack of quality data at present and difficulty in the quantification of impacts, but recognition is given to their relevancy and importance. Indicators related to the provision of infrastructure required for the extraction, transportation, refinery and storage of bitumen are excluded from this study. Although the primary target audience is South African road authorities, the approach can be adapted for use in any country.

2.2. Functional unit and system boundaries

The functional unit, representing the reference unit used to quantify indicator performance, is either one tonne crude oil bitumen depending on the relevant phase considered. This study comprises all the processes for the production and transportation of bitumen for a cradle-to-gate approach. In detail, the system boundaries include the following steps, shown in Fig. 1:

1 Crude oil extraction, which includes the requirements for extraction of crude oil from oil reserves in Africa and the Middle East and preparation for transportation.
2 Crude oil transportation, which includes the processes required for transporting crude oil by ship and pipeline to the relevant South African refineries.
3 Bitumen refinery and storage, which includes the processes required to process, refine and store paving-grade bitumen in South Africa.

2.3. Impact category indicators

For this study, the following impact category indicators are used:

- Carbon emissions (kg CO_2e/t)
- Energy use (MJ/t)
- Water use (l/t)
- Sulphur Dioxide emissions (kg SO_2/t)
- Nitrogen Oxides emissions (kg NOx/t)
- Particulate Matter emissions (kg PM_{10}/t)
- Volatile Organic Compounds emissions (kg VOC/t)

Allocation procedures specified in ISO [11] are not performed in this study.

2.4. Emissions

In this study, two separate types of emissions are focused on, namely environmental and social relevant emissions. Environmental emissions are "greenhouse" gasses (GHGs) affecting climate, covered under the Kyoto protocol, such as carbon dioxide and methane [12]. Social relevant emissions are those that predominantly affect human health such as Sulphur Dioxide (SO_2), Nitrogen Oxides (NOx), Particulate Matter (PM) and Volatile Organic Compounds (VOCs) [13].

2.4.1. Environmental emissions

To measure the environmental impact of the provision of pavement infrastructure, it is important to understand the various terms used to define it and its effect on the environment, such as "greenhouse gases", "CO_2", "CO_2e", and "carbon" as these terms may often be used interchangeably, and their meaning may become confusing [14].

A GHG is any gas in the atmosphere which adds to the greenhouse effect by absorbing and re-emitting heat, increasing the temperature of the planet above what it would normally be. Carbon dioxide is the most common GHG emitted from human activities in terms of quantity and total global warming potential (GWP). The GWP indicates the amount of warming a gas causes over several years (typically 100 years). CO_2e is a term used to describe the collection of greenhouse gases in a common unit. For any quantity or type of GHG, CO_2e signifies its equivalent CO_2 and the GWP impact on the atmosphere. Embodied carbon refers to the CO_2e associated with the non-operational phase of the project. This includes the emissions caused by the extraction, manufacturing and production of material, transportation, construction, maintenance, rehabilitation, deconstruction and disposal and end of life aspects which make up the materials of a pavement. The whole life carbon of pavement infrastructure is both the embodied carbon and the CO_2e associated with the use (i.e. operational) phase of the pavement [12,14].

2.4.2. Social emissions

Emissions from pavement infrastructure development which predominantly affect human health include SO_2, NOx, PM and VOCs. When these emissions are breathed in, they may cause noise, throat and airway problems, exacerbate asthma and in some cases cause cancer [13].

2.4.3. Legislation governing emissions in South Africa

The main legislation which governs these emissions in South Africa is the National Environmental Management: Air Quality Act (AQA) [15]. The act forms the framework for the control of air pollution and defines the air emissions limits for specific activities and processes. According to section 29 of the AQA, any production process which involves CO_2e emission over 0.1 Megatonnes annually is required to provide a pollution prevention plan to the Minister for approval. The processing of crude oil at a refinery requires an Atmospheric Emission License. Defined emission limits (taken as daily averages) are provided for refineries in South Africa under the AQA. These emission limits are 20 tonne/day for SO_2, 4 tonne/day for NOx and 1 tonne/day for PM.

2.5. Life cycle inventory of bitumen in South Africa

South Africa does not have any crude oil reserves and imports the raw material to produce bitumen. The major contributors to crude oil imports data as provided by the South African Department of Energy [16] are divided into two regions; Africa (52%) and Middle East (48%). Bitumen is shipped to predominantly two ports in South Africa, namely: Durban (77%) and Cape Town (23%). South Africa has four refineries:

- Natref (Sasol and Total) – Sasolburg,
- Enref (Engen) – Durban,
- Sapref (Shell and BP) – Durban), and
- Astron (old Chevron or Caltex) – Cape Town.

These refineries are responsible for the supply of bitumen to the South African market; however, they are not always able to guarantee stable bitumen supplies and refined bitumen is often imported.

2.6. Extraction

Oil extraction is the first process in bitumen production. The oil extraction process occurs in other countries from which South Africa imports (mainly African and the Middle Eastern countries) and the emissions so produced are specific to the extraction country and company. The International Association of Oil and Gas Producers (IPIECA) published guidance on voluntary sustainability reporting for oil and gas producers worldwide. This is a parallel program to the Voluntary National Review developed by the United Nations (UN) and allows interested companies to publish data for certain indicators related to, amongst others, the environmental and social impacts of their operations. Using these data, together with Eurobitume [5] estimates, typical values for the environmental and social emissions emitted and energy- and water-use related to crude oil extraction may be calculated, shown in Table 1. These indicator factors account for all background processes typically required for crude oil extraction including preparation for transportation. These estimates have been obtained from various sources and do not necessarily represent the view or findings of the respective companies referenced. Data quality indicators (DQIs) are used in this study to assess the quality of data collected according to the applicable ISO guidance [11]. To do this, an adapted data quality matrix [17] is used and applied to all data in this study. The data quality matrix is provided as supplementary information.

Table 1
Weighted average indicator factors for crude oil extraction per tonne.

Indicators	Unit	Average* [18–26]
Environmental Related Indicators		
Carbon Emissions	kg CO_2e/t	157.38
Energy Use	MJ/t	1450.28
Water Use	l/t	290.92
DQI		75%
Social Related Indicators		**European average**[5]
Sulphur Dioxide Emissions	kg SO_2/t	0.4
Nitrogen Oxides Emissions	kg NOx/t	0.25
Particulate Matter Emissions	kg PM_{10}/t	0.02
Volatile Organic Compounds Emissions	kg VOC/t	0.33
DQI		72%

* Weighted average for Africa and the Middle East.

2.7. Transport

2.7.1. Shipping

Crude oil tankers are available in a variety of sizes, namely PANAMAX, AFRAMAX, SUEZMAX, VLCC and ULCC. In this study, crude oil is assumed to be transported using an AFRAMAX vessel size of between 80 - 120 Dead Weight Tonnes (DWT). This vessel size is popular amongst oil companies [27] and assumed to be a conservative representation of typical vessel size from all regions to South Africa.

Typical AFRAMAX vessel specifications are used for this study [28]. The fuel consumption is calculated on the assumption that the ship is fully loaded for the trip to South Africa, and the return trip is not considered as part of the overall journey. An adjustment is made in that 28% of South Africa's bitumen production is exported [29]. It is assumed then that the ship would be loaded for its return trip from South Africa and emissions related to the return trip are embodied in export products. The data for the marine engine emissions produced by the shipping vessel is obtained from the European Environment Agency (EEA) [30]. Consumption of fuel to load and discharge crude oil or petroleum products from the vessel are vessel- and port-specific. Accurate data are not available for South African ports and typical conservative values [5] are used for the analysis. To determine transportation distance, a port to port distance calculation tool [31] is used. Missing information is supplemented with distance measurements. EEA [30] provides estimates for social-related emissions for typical marine fuel used. It is noted that the type of marine fuel used affects these estimates. Using this information, typical indicator factors may be calculated for shipping one tonne of crude oil from all regions, shown in Table 2.

Table 2
Weighted average indicator factors for shipping one-tonne crude oil.

Indicators	Unit	Weighted Average
Environmental Related Indicators		
Carbon Emissions	kg CO_2e/t	11.12
Energy Use	MJ/t	140.15
Water Use	l/t	48
DQI		86%
Social Related Indicators		
Sulphur Dioxide Emissions	kg SO_2/t	0.13
Nitrogen Oxides Emissions	kg NOx/t	0.51
Particulate Matter Emissions	kg PM_{10}/t	0.01
Volatile Organic Compounds Emissions	kg VOC/t	0.02
DQI		86%

Table 3
Average pipeline transport indicator factors for one-tonne crude oil for coastal and inland scenarios [33,34].

Indicators	Unit	Coastal average	Inland average
Environmental Related indicators			
Carbon Emissions	kg CO_2e/t	0.30	11.77
Energy Use	MJ/t	1.01	39.6
Water Use	l/t	0.19	7.26
DQI		74%	
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/t	0	0.1
Nitrogen Oxides Emissions	kg NOx/t	0	0.05
Particulate Matter Emissions	kg PM_{10}/t	0	0
Volatile Organic Compounds Emissions	kg VOC/t	Not reported	Not reported
DQI		76%	

These estimates are based on a range of assumptions and simplifications. This applies for the Eurobitume [5] database which only considers one shipping vessel specification. More accurate results may be obtained if better quality data is acquired reflecting the actual shipping specifications of South Africa's oil imports. It is further worth noting that the relatively long shipping distances to South Africa significantly increase the environmental and social burden of imported oil compared to most countries.

2.7.2. *Pipeline*

South Africa makes use of various pipelines to transport crude oil from the ships to the four refineries. For instance, ships offloading at Durban Port are required to offload at an oil terminal roughly 2.5 km offshore of the Bluff. Oil is pumped from the terminal through to the Enref and Sapref refineries, and further to Natref in Sasolburg with similar operations used for Astron in the Cape. Pipelines transport 100% of crude requirements to refineries in South Africa [32]. Pipeline lengths are obtained from Transnet [32].

The energy required to pump crude oil to the different refineries is calculated using conservative data provided by Eurobitume [5]. It is noted that the energy use from the Eurobitume [5] database is 260% higher than that from the Eurobitume [4] database. This reflects the assumptions made and the effect different pipeline specifications and topography have on the energy consumption. Eskom [33] provides estimates for social-related emissions for electricity obtained from the electrical grid. Emissions are provided for two scenarios, namely coastal (average for Astron, Sapref and Enref) and inland (Natref). Typical factors are shown in Table 3 for the transportation of one-tonne bitumen via pipelines.

More accurate data is required for the pipelines in South Africa, considering the energy efficiency of pump stations, the effect of topography (with Sasolburg being 1500 m above sea level, for instance), and the typical specifications of the various pipelines used to transport crude oil.

Table 4
Average refinery and storage environmental indicator factors for one-tonne bitumen production.

Indicators	Unit	Average
Environmental Related Indicators		
Carbon Emissions [38,39]	kg CO_2e/t	53.09
Energy Use	MJ/t	610
Water Use	l/t	342.5
DQI		75%
Social Related Indicators		
Sulphur Dioxide Emissions	kg SO_2/t	0.6
Nitrogen Oxides Emissions	kg NOx/t	1.75
Particulate Matter Emissions	kg PM_{10}/t	Not reported
Volatile Organic Compounds Emissions	kg VOC/t	0.28
DQI		76%

2.8. *Bitumen refinery and storage*

To produce bitumen, a complex refinery is required to conduct a straight-run distillation process on crude oil which produces a range of petroleum products. Bitumen is a major product of this process, estimated at 28.5% bitumen yield by mass [5].

The energy used for the distillation process is not well reported, however, Eurobitume [5] estimates that 510 MJ/t is required and includes consideration of various back-ground processes such as crude oil handling, desalting, flaring, loading area, general heating and lighting. A further 100 MJ/t is estimated for the storage of bitumen. CONCAWE [35] data highlights that of the total energy used in a refinery, 96% is obtained from burning bi-products (84% refinery gas) and heavy fuel oil (12%). The remaining 4% is from the electrical grid. Eurobitume [5] disregards the energy obtained from the electricity grid. Alternative opinions [3] state that South African refineries may use heavy fuel oil as the primary fuel type. Based on this information, it was decided to use heavy fuel oil (90%) as the main fuel type, supplemented with estimated distributions for refinery gas (6%) and electricity (4%) from the electrical grid.

Each of these energy sources was further investigated. Using calorific values of 40.4 MJ/kg for heavy fuel and 49.5 MJ/kg for refinery gas [36], the consumption of energy for the production of bitumen by straight-run distillation may be calculated. Social related emissions for typical refinery processes in South Africa are obtained from Sapref [37]. Table 4 shows the indicator factors for one-tonne bitumen production.

The total emissions of 53.09 kg CO_2e/t for the refinery and storage of bitumen may be compared to the estimate by Eurobitume [5] of 25.55 kg CO_2e/t. The increase in emissions is related to the differences in energy source distributions and higher emissions factors for South African electricity production, amongst others. It is further worth noting that the emissions related to bitumen refinery between the Eurobitume [4] (46.03 kg CO_2e/t) and Eurobitume [5] (25.55 kg CO_2e/t) represent a reduction of roughly 46% and highlights the requirement for further research and the need for quality data.

3. Results

The results of the analysis are provided for the emissions, energy- and water-use for bitumen production in South Africa considering both coastal and inland scenarios, shown in Table 5.

An analysis of the phases which contribute most to the carbon emissions of bitumen in South Africa was conducted. Fig. 2 shows the contribution of each phase.

It is seen that the extraction phase contributes to the majority of the carbon emissions of bitumen production for both coastal and inland scenarios, followed by the refinery and storage and transportation phases. Similar results are obtained when evaluating the contributions for other indicators.

Table 5
Indicator factors for bitumen in South Africa.

Scenario	Unit	Extraction	Transportation	Refinery and storage	Total
Carbon Emissions					
Coastal	kg CO_2e/t	157.38	11.42	53.09	221.89
Inland	kg CO_2e/t		22.89		233.36
Energy Use					
Coastal	MJ/t	1450.28	141.15	610	2201.40
Inland	MJ/t		179.75		2240.00
Water Use					
Coastal	l/t	290.92	48.19	342.50	681.61
Inland	l/t		55.26		688.68
Sulphur Dioxide Emissions					
Coastal	kg SO_2/t	0.40	0.13	0.60	1.13
Inland	kg SO_2/t		0.23		1.23
Nitrogen Oxides Emissions					
Coastal	kg NOx/t	0.25	0.51	1.75	2.51
Inland	kg NOx/t		0.56		2.56
Particulate Matter Emissions					
Coastal	kg PM_{10}/t	0.02	0.01	Not reported	0.03
Inland	kg PM_{10}/t				
Volatile Organic Compounds Emissions					
Coastal	kg VOC/t	0.33	0.02	0.28	0.68
Inland	kg VOC/t				

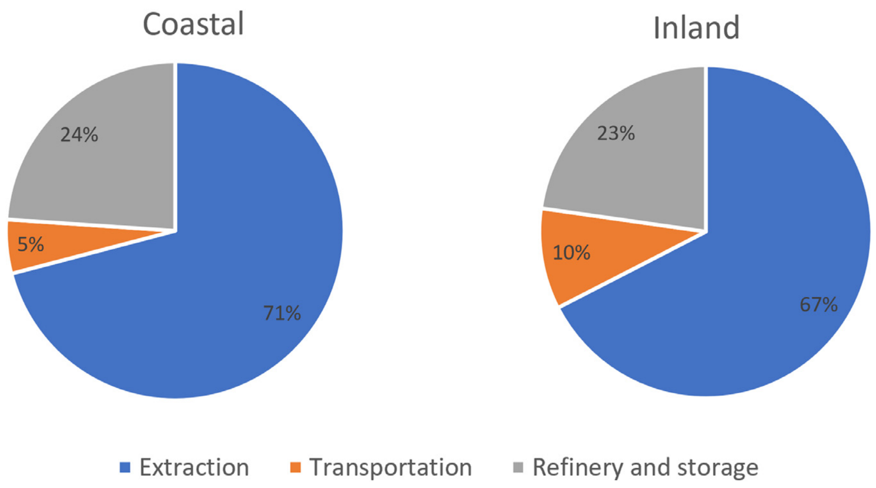


Fig. 2. Contribution of phases to the carbon emissions of bitumen in South Africa.

It is noted that the results presented in this study have made use of proxy data in the absence of accurate local data. As described in literature, the use of proxy data to fill gaps in research is a common approach implemented in LCA studies where the driver of the study is a relative comparison and not quantifying absolute numbers. However, as bitumen has been identified as a leading material contributing to emissions [8], the need for accurate estimates is emphasised.

The use of proxy data was especially required for the refinery and storage phases and is related to the energy requirements for bitumen processing. Participation of local refineries could enhance the quality of available data and remove the need to rely on external estimates.

3.1. *Data validation*

To validate the results, a comparison may be made to similar life cycle inventories related to penetration grade bitumen production, shown in Table 6.

The carbon emissions for bitumen production from crude oil in South Africa are generally higher than in other regions in the world. Various factors affect these estimates, detailed in the sensitivity analysis shown in the following section.

3.1.1. *Sensitivity analysis*

To determine the parameters and assumptions which most greatly influence the carbon emission values of bitumen production in South Africa, a sensitivity analysis was conducted. The results of this analysis highlight the areas which predominantly require additional research to ensure accurate estimates are available.

The region and typical associated extraction processes contribute significantly to the carbon emissions of bitumen production. In the sensitivity analysis, typical extraction embodied carbon values for the Former Soviet Union and South America [5] were used as alternative scenarios. Using these estimates, a 25% reduction in extraction embodied carbon estimates per tonne crude oil was obtained.

The relatively low shipping estimate is due to the type of vessel considered in the calculations and is not a true reflection of the shipping reality. This statement is however also applicable to the shipping estimates of Eurobitume [5]. In the sensitivity analysis, the shipping specifications from the Eurobitume [5] analysis were used as the alternative scenario and a 12.5% increase in carbon emissions was calculated for crude oil shipping per tonne.

The energy estimate required to pump crude oil greatly affects the environmental burden of transportation. The lengthy pipeline used to pump crude oil to Sasolburg may have a range of pipeline diameters,

Table 6
Comparison of carbon emissions for straight-run bitumen production from crude oil.

Life Cycle Inventory	Unit	Extraction	Transportation	Refinery and storage	Total
Hammond and Jones [17]	kg CO_2e/t	–	–	–	191.00
Eurobitume [4]	kg CO_2e/t	99.14	30.08	45.03	174.25
Eurobitume [5]	kg CO_2e/t	90.14	21.25	25.41	136.80
South Africa – Import Coastal	kg CO_2e/t	157.38	11.42	53.09	221.89
South Africa – Import Inland	kg CO_2e/t	157.38	22.89	53.09	233.36

Table 7
Key indicators for reporting.

Key Indicators	Unit
Crude oil carbon emissions[1]	kg CO_2e/t
Comprehensive energy consumption per tonne of bitumen[2]	MJ/t
Freshwater consumption per tonne of bitumen	l/t
Total water consumption per tonne of bitumen	l/t
Emissions per tonne of bitumen[3]	kg gas/t
Emissions to water per tonne bitumen[4]	ppm/t
Waste generation per tonne bitumen	kg/t
Job creation in the bitumen production sector	Jobs/year
Educational outreach	
Women empowered[5]	

[1] dependant on source and transportation method of crude oil to the refinery.
[2] Including energy source distributions.
[3] Key emissions include CO_2e, SO_2, NOx, PM and VOCs, amongst others.
[4] Key emissions include wastewater, hazardous waste (e.g. phenol and other aromatic compounds) and oil effluent, amongst others.
[5] May be assessed qualitatively using a typical empowerment index and monitored yearly to evaluate performance.

pump stations specifications, various topographical variations and as a result of a different energy requirement to pump crude oil. Carbon emission estimates are directly related to energy consumption and a change in energy distribution proportionally affects the embodied carbon of crude oil transport via pipelines. Using Eurobitume [4] estimates as the alternative scenario, a 65% decrease in embodied carbon estimates is calculated.

What further influences the accuracy of the results are basing refinery and storage estimates on typical international values. However, it is worth noting that estimates for the refinery and storage phases may be reduced if accurate energy distributions are known. Using an energy distribution change favouring heavy fuel oil as the main energy source for the alternative scenario reduced the carbon emissions of bitumen refinery and storage by 9.7%. This highlights the need for the industry to partake by voluntarily releasing information related to production factors.

3.2. Guidance for refineries and road authorities in South Africa

It is proposed that refineries monitor, measure and voluntarily publish data on the following key indicators of bitumen production, shown in Table 7.

It is further proposed that refineries use carbon emission estimates for crude oil to benchmark the carbon footprint for crude they use. This may assist overall decision making and on where to source crude from. There also exists a need for road authorities such as the South African National Roads Agency SOC Limited (SANRAL) to promote voluntary monitoring and publication actions and provide a platform for the collection and delineation of data from industry and researchers.

Conclusions

The following conclusions were drawn from the study:

- The inventory provided in this study is based on reasonable quality data and provides rational estimates for certain environmental and social impacts for bitumen production in South Africa. This inventory may be used to enhance prediction estimates for assessments where paving-grade bitumen is utilised.
- There is a drive within South African roads authorities to promote sustainable technologies and practices. However, targeted efforts are required from roads authorities to focus on the supply chain of bitumen and further to asphalt production. These authorities would do well to support academic and industry research aimed at developing a database of quality data.
- There is a need to create an online platform to promote sustainable practices. This online platform may take the form of a SANRAL webpage that is open to the public to provide a knowledge base for the pavement community including contractors, government agencies, private consultants as well as future industry members. Experiences with Pavement Interactive, a similar online platform, has shown great reach and success [40].
- Certain social indicators are not yet well understood, which may carry little meaning to the practitioner. Further research is required to develop valid quantification and impact models.
- Development of a standard pavement LCA is required for a cradle-to-grave scenario. This LCA needs to be developed specifically to South Africa.
- Holistic sustainability is only achieved if all three tenets of sustainability (i.e. economic, environmental, social) are confidently evaluated. Further research is required to develop a model that quantifies holistic sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.treng.2020.100019.

References

[1] FHWA, Federal highway administration, Life Cycle Assessment of Pavements, Tech Brief, Washington, D.C., USA, 2014 FHWA-HIF-15-001.
[2] N. Santero, E. Masanat, A. Horvath, Life cycle assessment of pavements. Part I: critical review, Resour. Conserv. Recycl. 55 (9–10) (2011) 801–809.
[3] J. Harvey, A. Saboori, M. Dauvergne, W.JvdM. Steyn, A. Jullien, H. Li, Comparison of new pavement construction GHG and energy impacts in different regions, Papers From the International Symposium on Pavement Life Cycle Assessment, University of California, California, USA, 2014 ISBN 978-0-692-29357-7.
[4] Eurobitme, The Eurobitume Life-Cycle Inventory for Bitumen, Version 2, European Bitumen Association, Brussels, Belgium, 2012.
[5] Eurobitme, The Eurobitume Life-Cycle Inventory for Bitumen, Version 3.1, European Bitumen Association, Brussels, Belgium, 2020.
[6] T.M. Gulotta, M. Mistretta, F.G. Practicò, A life cycle scenario analysis of different pavement technologies for urban roads, Sci. Total Environ. 673 (18) (2019) 585–593.
[7] S. Bressi, G. D'Angelo, J. Santos, M. Giunta, Environmental performance analysis of bitumen stabilized ballast for railway track-bed using life cycle assessment, Constr. Build. Mater. 188 (2018) 1050–1064.

[8] M. Giunta, M. Mistretta, F.G. Practicò, M.T. Gulotta, Environmental sustainability and energy assessment of bituminous pavements made with unconventional materials, in: Proceedings of the 5th International Symposium on Asphalt Pavements and Environment (APA), 2020, pp. 123–132. https://doi.org/10.1007/978-3-030-29779-4_12.

[9] M. Vila-Cortavitarte, P. Lastra-Gonzalez, M.A. Calzada-Perez, I. Indacoechea-Vega, Analysis of the influence of using recycled polystyrene as a substitute for bitumen in the behavior of asphalt concrete mixtures, J. Clean. Prod. 170 (2018) 1279–1287.

[10] U. Berardi, Clarifying the new interpretations of the concept of sustainable building, Sustain. Cities Soc. 8 (2013) 72–78.

[11] ISO, International Organisation for Standardisation, ISO 14040, Environmental Management - Life Cycle Assessment - Principles and Framework, ISO, Geneva, Switzerland, 2006.

[12] IPCC, Summary for policymakers, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, England, 2007.

[13] WHO, World Health Organisation, Air Quality Guidelines Global Update: Particulate Matter, Ozone, Nitrogen Dioxide and Sulphur Dioxide, WHO, Copenhagen, Denmark, 2005 EUR/05/5046029.

[14] M. Brander, Greenhouse gases, CO_2, CO_2e, and carbon: what do all these terms mean? Ecometrica (2012) Edinburgh, Scotland. Available at Ecometrica.com.

[15] AQA, National Environmental Management: Air Quality Act. Act No. 39, Department of Environmental Affairs, Pretoria, South Africa, 2004.

[16] SA-DoE, Annual Report 2018/2019, DoE, Pretoria, South Africa, 2019 Available at Energy.gov.za.

[17] Hammond, G.P., Jones, C.I., 2019. Embodied energy and carbon – the inventory for carbon and energy database. Available at Circularecology.com

[18] CNOOC, Environmental, social and governance report, Investor Relations Department of CNOOC Limited, Beijing, China, 2018 CNOOCAvailable at Cnoocltd.com.

[19] Eni, Sustainability report. Eni, Rome, Italy, 2018 Available at Eni.com.

[20] Equinor, Sustainability report, Equinor. Stavanger, Norway, 2019 Available at Equinor.com.

[21] Occidental, 2018. Occidental petroleum corporation - annual summary, environmental data. Occidental petroleum. Houston, Texas. Available at Oxy.com.

[22] Chevron, 2018. Sustainability report. Chevron. California, USA. Available at Chevron.com.

[23] BP, 2019. Sustainability report. BP, London, UK. Available at Bp.com.

[24] Noble Energy, 2018. Sustainability report. Noble Energy. Houston Texas. Available at Nblenergy.com.

[25] Tullow Oil, 2019. Sustainability Report. Tullow Oil. London, UK. Available at Tullowoil.com.

[26] PDO, Sustainability Report 2018 – Building a Sustainable Future, OPD, Muscat, Sultanate of Oman, 2018 Available at Pdo.co.om.

[27] US EIA, 2014. United Stated Energy Information Administration. Hamilton, M.T. London Tanker Brokers' Panel. US EIA. Viewed 05/05/2020. Available at Eia.gov/todayinenergy.

[28] Wärtsilä, 2020. WSD 42 111K Data Sheet. Wärtsilä. Viewed 01/04/2020. Available at Wartsila.com.

[29] SABITA, South African bitumen association, Best Practice Guide for the Procurement and Importing of Bitumen, Edition 1, SABITA, Cape Town, South Africa, 2013 Available at Sabita.co.za.

[30] EEA, European Environment Agency, Air Pollutant Emission Inventory Guidebook. Technical Guidance to Prepare National Emission Inventories, EEA, Luxembourg, Luxembourg, 2019 ISSN 1977-8449.

[31] SeaRates, 2020. Port to port distance calculation tool. Searates. Viewed 21/04/2020. Available at Searates.com

[32] Transnet, 2019. Pipelines - Information Sheet. Transnet, Johannesburg, South Africa. Available at Transnet.net.

[33] Eskom, Environmental implications of using or saving electricity, Eskom Holdings, Sandton, South Africa, 2014 Available at Integratedreport.eskom.co.za.

[34] R. Inglesi-Lotz, J.N. Blignaut, Electricity intensities of the OECD and South Africa: a comparison, Renew. Sustain. Energy Rev. 16 (7) (2012) 4491–4499.

[35] CONCAWE, Sulphur Dioxide Emissions From Oil Refineries in Europe. Report no. 5/18, CONCAWE, Brussels, Belgium, 2018.

[36] UN – ESY, United Nations- Energy Statistics Yearbook, Statistic Division. UN, Brussels, Belgium, 2017.

[37] Sapref, 2017. Sustainability report - A report for our stakeholders. Sapref. Durban, South Africa. Available at Sapref.com

[38] IMO, International Maritime Organisation, Third IMO Greenhouse Gas 2014 Study, IMO, London, UK, 2015.

[39] Volker-Quaschning, Specific Carbon Dioxide Emissions for Various Fuels, Volker-Quaschning, 2015 Viewed 28/05/2020. Available at Volker-quaschning.de.

[40] S.T. Muench, Y.Y. Lin, S. Katara, A. Armstrong, Roadprint: practical pavement life cycle assessment (LCA) using general available data, in: International Symposium on Pavement LCA, Davis, California, 2014, pp. 249–262.