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NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Environmental impact of railway development

The Standard Gauge Railway in Tanzania

Master's thesis in Industrial Ecology
Supervisor: Edgar Hertwich
July 2020

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Abstract

Current railway activities in Africa suffer from poor track condition and lack of maintenance, but there is potential for rail transport growth for both passengers and freight. The aim of this thesis is to evaluate the environmental impact of a railway development in Africa.

The Standard Gauge Railway (SGR) in Tanzania, a railway line currently under construction, was identified as a relevant rail system to study from a life cycle perspective. Materials and energy requirements were collected and estimated from various sources of information to build a model representing the SGR (the SGR-model). A life cycle assessment (LCA), methodology used to evaluate environmental impacts, was conducted for this SGR-model. Rolling stock, its operation, and infrastructure were evaluated over 60 years of operation. To cover several types of environmental damages resulting from the construction and operation of the railway line, eight impact categories have been included in this environmental assessment.

The operation phase was found to have the highest contribution to climate change, fossil depletion, particulate matter formation, and terrestrial acidification. These impacts essentially come from the use of fossil fuels in the electricity supply mix. When analysing environmental impacts of the infrastructure, materials stood out as having the highest contribution to freshwater eutrophication, mineral resource depletion, and human toxicity. The use of steel and copper in the track and power and signalling system are the main contributors to these impacts. In addition, several other activities have also been identified as contributing significantly to environmental impacts of the infrastructure: transport of materials by lorry, land clearance as well as land transformation. Regarding the rolling stock, goods wagons generate most of its environmental impacts.

Scenarios based on the LCA model have been developed. Several electricity supply mixes were investigated, lifetime of railway components (sleepers, rails, and pads) and goods wagons was extended, use of secondary steel was introduced in the maintenance phase, and transport of materials was decreased. Results indicate that increasing the share of renewables in the electricity supply mix leads to the most significant impact reduction in climate change, fossil depletion, particulate matter formation and terrestrial acidification. Despite having a more limited impact reduction, the use of secondary steel and lifetime extensions have the potential to reduce freshwater eutrophication, human toxicity, and mineral resource depletion impacts. A combination of these various strategies is therefore suggested to improve the overall environmental performance of the SGR in Tanzania.

Preface

This thesis has been written during spring 2020 in the MSc Industrial Ecology at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU).

This thesis was the opportunity to apply and extend the knowledge about environmental impacts of rail transport I acquired during the project written in autumn 2019. Choosing a railway line to study was not an easy task, building its model needed some creativity but this gave me an insight of what it is to do research in Industrial Ecology and which challenges are encountered.

I would like to express my gratitude to my academic advisor, Professor Edgar Hertwich, for his support, guidance, and advice all along my thesis work.

I am grateful to Dr Albert Lau, from the Department of Civil and Environmental Engineering at NTNU, and Alf Helge Løhren, Civil Engineer, PhD working at Bane NOR, for their valuable help by sharing their knowledge and answering all my technical questions regarding railway engineering.

I would also like to thank the International Offices from NTNU and from my home university, Ecole Centrale de Nantes in France, for offering me this opportunity to enrol in a double degree programme in Norway, live new experiences, and learn about a new culture.

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List of Abbreviations (or Symbols)

AfDB	African Development Bank Group
EPD	Environmental Product Declaration
ESIA	Environmental and Social Impact Assessment
GHG	Greenhouse Gas
GWP	Global Warming Potential
HSR	High-Speed Rail
IEA	International Energy Agency
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MGT	Million gross tonnes
RoW	Rest of the Word
SGR	Standard Gauge Railway
TRC	Tanzania Railways Corporation
UIC	Union Internationale des Chemins de fer (International union of railway)

1 Introduction

1.1 Context

1.1.1 Environmental impact of transport and rail transport

Environmental pressures from transport result from various sources such as automobile traffic responsible for greenhouse gas (GHG) emissions, noise, acidification on existent buildings, and local as well as global air pollution (Steg and Gärling, 2007, chap. 2). According to the Fifth Assessment Report of the International Panel on Climate Change (IPCC), direct emissions from the transport sector represented 14% of total anthropogenic GHG emissions in 2010 (IPCC, 2014). Moreover, the International Energy Agency (IEA) statistics in 2017 detail that transport is responsible for about a quarter of total CO_2 emissions from fuel combustion (IEA, 2019a) and a third of total final energy consumption (IEA, 2019c).

However, transport contribution to the Sustainable Development Goals is well recognized: transport plays an essential role in regional development, it enables access to education, health, sanitation, and creates employment opportunities (UN-Habitat, UNEP and SLoCaT, 2015; SLoCaT, 2019). Among the different types of motorized transport modes, rail can be an opportunity to reduce direct GHG emissions and save energy. Indeed, rail contributes to less than 2% of total direct emissions from the transport sector (IPCC, 2014) and its energy consumption is 2% of total transport energy use while transporting about 8% and 7% of global passengers and freight (IEA, 2019b).

1.1.2 Railway in Africa

Railway network densities around the world vary substantially depending on the region considered. Bullock (2009, p.6) reports that railway network densities vary from 30 to 150 km of track per million capita in several Sub-Saharan countries up to 1500 km of track per million capita in Australia and Canada.

Railway activity in Africa is low compared with global railway activity. Based on provisional statistics from the International Union of Railway, it represents only 0.5% and 2% of worldwide passenger and freight transport by rail (UIC, 2020). Indeed, the railway network in Africa is formed of disconnected lines in rather poor condition especially in Sub-Saharan African countries (excluding the Republic of South Africa) due to a prioritisation of roads, a lack of railway maintenance and expertise, and destruction of infrastructure during conflicts (Bullock, 2009, pp. 9–12; AfDB, 2015, p. 53). Moreover, many African railway lines were built more than 100 years ago (end of 19th and beginning of 20th centuries, i.e. during colonial times) and only a handful of railway lines were built in the second part of the 20th century such as the TAZARA line (connecting Tanzania and Zambia), a large-scale railway project supported by China in the 1970s (Bullock, 2009, p. 5).

Despite the current low rail transport activity, there is a high potential for railway development in Africa which is experiencing a rapid growth of population and economy resulting in need for transport infrastructure (AfDB, 2015). Rail transport could have a central role in the development of the continent (Chandid, 2014).

1.1.3 Life cycle assessment of rail transport

Even if rail transport offers energy-efficiency and potentials for GHG emissions reduction, large quantities of materials are required in the construction and maintenance phases of railway infrastructures (Svensson and Eklund, 2007; Wang *et al.*, 2016) and the case of railway development in Africa is an example of developing regions which need to build infrastructure resulting in demand of material and energy resources, and GHG emissions (Müller *et al.*, 2013).

To evaluate the global environmental impact of railway, all the life cycle activities (raw materials production, construction/manufacturing, usage phase, maintenance, end-of-life) need to be taken into consideration and include the rolling stock, infrastructure and fuel (electricity/diesel) required for operations (Chester and Horvath, 2009). One methodology available to assess environmental impacts from a life cycle perspective is life cycle assessment (LCA) (ISO, 2006a, 2006b).

Rail development could benefit from life cycle environmental impact studies in decision-making processes related to the construction, operation and disposal stages of rail transport systems (de Bortoli, Bouhaya and Feraille, 2020) as well as processes related to the mitigation of emissions and energy use (Chester and Horvath, 2009).

1.2 Aim and scope

In the autumn semester project (Rousseau, 2019), a life cycle inventory of materials and energy requirements of a railway line was developed based on archetypes of various components included in a rail transport system. The global warming potential impact of a fictive scenario was also evaluated using LCA methodology. Literature review findings and results from the project described that the electricity supply mix has a strong influence on global warming potential of the railway operation, materials have a high contribution to the railway environmental impacts, and material efficiency was suggested as one strategy to reduce these environmental impacts.

The objective of this thesis is to apply the knowledge about LCA of railway acquired during the project to investigate the potential future impacts of a rail line or regional railway system in Africa and illustrate the method of scenario-based LCA. The scenario framework gives the opportunity to reduce the environmental impacts of the identified railway line or system.

The first step of this thesis was to choose a railway development to study. The identified railway line is the Standard Gauge Railway (SGR) in Tanzania which is currently under construction. To evaluate the potential environmental impacts of the SGR in Tanzania and illustrate the method of scenario-based LCA through alternative scenarios development, the following research questions are addressed:

1. What are the main materials and energy requirements for the construction, maintenance, and operation of the SGR in Tanzania?
2. How do the different life cycle stages, railway infrastructure components, and rail vehicles contribute to the environmental impacts?
3. How do clean energy, material efficiency strategies, and alternative materials influence the environmental impacts of the rail transport system?

4. What are the trade-offs between climate change mitigation and other environmental impact categories?

1.3 Outline

This thesis is divided into eight chapters including the introduction. Chapter 2 is a review of existing literature regarding life cycle models of rail transport and main findings about environmental impacts. Chapter 3 describes methods and materials used in this thesis. In this chapter, LCA methodology is further explained, a description of the SGR in Tanzania is provided, and the life cycle model of the SGR is introduced (the SGR-model). Chapter 4 is the life cycle inventory of the SGR-model and includes data collection, assumptions, and estimates of material and energy requirements. Chapter 5 presents the results of the environmental impact assessment. Alternative scenarios are developed in Chapter 6 and their corresponding environmental impacts are given. Lastly, results and the SGR-model are discussed in Chapter 7 and conclusions as well as suggestions for further research are presented in Chapter 8.

2 Literature

Reading and understanding literature is a preliminary task to become familiar with environmental studies of railway and understand how they are performed to be able to achieve the main objective of this thesis, which is to evaluate the environmental impacts of the SGR in Tanzania.

This chapter is therefore an investigation of some relevant scientific literature and technical reports related to railways and more specifically their life cycle environmental impacts. The purpose of this chapter is to identify the main elements to consider when studying railway from an environmental perspective and building a life cycle model of a railway line. Moreover, main results regarding environmental impacts of rail transport are described.

2.1 Definitions

Before introducing the literature, definitions of some technical terms used in this chapter or in this thesis are provided in this section.

Rail vehicles transporting passengers or freight are guided by railway tracks. Two types of railway tracks are found (Kiani, Parry and Ceney, 2008):

- Ballasted track made of ballast (crushed stones, aggregates) and rails placed on sleepers and fixed with fastenings.
- Slab track or ballastless track where a concrete layer replaces ballast.

Rail and more generally transport of passengers and freight can be defined in the following way (Spielmann *et al.*, 2007; The International EPD® System, 2019):

- passenger-kilometres (pkm), calculated by multiplying the number of passengers by the distance travelled.
- net tonnes-kilometres (tkm), calculated by multiplying the freight load in tonnes by the distance of transport.

2.2 Environmental studies of railway

Despite improving movements of goods and people, rail transport is responsible for several types of environmental impacts such as GHG emissions. GHG emissions related to rail transport are classified into three categories by Saxe et al. (2016):

- GHG emissions from materials, waste, and energy to build, maintain, and operate the infrastructure.
- GHG emissions and savings due to changes in mobility patterns.
- GHG emissions and savings due to land use changes because of the new rail infrastructure.

These three categories, even if attributed to GHG emissions by Saxe et al. (2016), could also be applied to other types of emission or resource consumption resulting from the construction and operation of a railway line. The last two categories referring to secondary effects, although necessary to provide a comprehensive environmental impacts study of a railway project (Saxe *et al.*, 2016), are excluded from the scope of this thesis. Only the first category of impact is considered, and literature gathered and described in this chapter is therefore focused on the impacts coming from the railway line or network itself.

2.2.1 Aims and scopes

As pointed out by Ebrahimi (2014), environmental studies of rail transport cover a diverse panel of systems being studied (rail components, specific infrastructure sections for instance bridges and tunnels, rolling stock). This idea can be extended to classify railway environmental studies depending on the type of system considered and especially how large the system is and how many entities are analysed.

Three components compose a rail transport system: infrastructure, rolling stock, and operation (Spielmann *et al.*, 2007).

As already identified in the semester project (Rousseau, 2019), the infrastructure is usually composed of the following elements: track foundations/roadbed, tracks, electrification equipment to supply power and ensure signalling and telecommunication, civil engineering structures such as bridges and tunnels, and buildings (e.g. passenger stations, freight terminals, maintenance and repairing sites) (Von Rozycki, Koeser and Schwarz, 2003; Stripple and Uppenberg, 2010). It is also possible to find larger system boundaries for the infrastructure including service activities related to the transport activity such as insurance buildings (Chester, 2008).

Regarding the rolling stock, there exist several types of rail vehicles for passenger and freight transport: passenger trains, locomotives and goods wagons. When the rolling stock is included in rail transport studies, it is often handled by using processes available in life cycle databases and modifying these processes to fit the characteristics of the specific vehicles included in system being analysed (for example, total weight of the vehicle, weight of the vehicle per seat, material composition) (Åkerman, 2011; Grossrieder, 2011; Yue *et al.*, 2015). However, the material composition of the rolling stock of the Mumbai suburban railway was collected from the manufacturer (Shinde *et al.*, 2018).

Operational phase consists of operations of vehicles and infrastructure including the fuel consumption (electricity/diesel) as well fuel production and its supply chain (Chester and Horvath, 2009). Additional energy consumption from passengers going to and leaving from the train stations can also be included (von Rozycki, Koeser and Schwarz, 2003).

Nevertheless, environmental assessments of railway do not necessarily include the three components (infrastructure, rolling stock, and operation). Some studies focus only on the railway infrastructure such as for the Tours-Bordeaux railway in France (de Bortoli, Bouhaya, & Feraille, 2020) while some other works consider the entire rail transport system such as the study of Beijing-Shanghai High Speed Rail (HSR) in China (Yue *et al.*, 2015) and the Bothnia Line in Sweden (Stripple and Uppenberg, 2010). It is worth noticing that these three lines are existing lines in operation. However, it is also possible to study projected lines such as the California HSR (Chang and Kendall, 2011).

As mentioned previously, the focus of a study can specifically be on infrastructure sections or look even closer by focusing on components (Eslami Ebrahimi, 2014). Designs of railway bridges in Sweden have been analysed (Du and Karoumi, 2013; Thiebault, Du and Karoumi, 2013) as well as effects of railway tunnels on railway energy consumption and carbon emissions (Pritchard and Preston, 2018). Impacts of railway components are also described by comparing ballasted and ballastless tracks (Kiani, Parry and Ceney, 2008; Milford and Allwood, 2010), reinforced and timber sleepers (Crawford, 2009) or studying the electrification system of a railway line (Eslami Ebrahimi, 2014). These studies at different levels can provide useful information which can further be used as secondary sources of data for a larger study: for example, the study of the construction of the California HSR project collects quantities of materials and energy required for the track from the track study written by Kiani, Parry and Ceney (2008) (Chang and Kendall, 2011).

The possible study categories for an environmental study of railway are shown in Figure 2.1. Some studies directly fit in one of the boxes, but it is also possible to combine categories if for example both the rolling and its operation are analysed but the infrastructure is excluded.

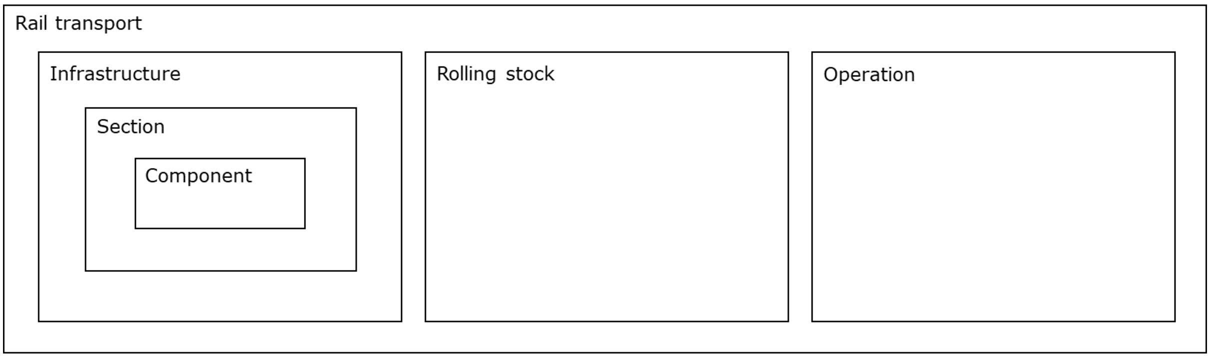

Figure 2.1 - Possible categories for environmental studies of railway

In addition to be diverse in terms of system being studied, environmental studies of railway cover various spatial areas. Some environmental assessments are performed at a national level. Mottschall and Schmied (2013) evaluated the GHG emissions from the rail infrastructure and rolling stock in Germany, and Merchan, Belboom and Léonard (2020) conducted a life cycle assessment of the rail freight transport in Belgium. Moreover, a Material Stock and Flow Analysis (MFSA) study was performed in China to estimate the material quantities requirements in the Chinese High Speed Rail network (Wang *et al.*, 2016). However, it can be noted that many railway environmental studies focus on a specific railway line. As examples, the study of the Bothnia Line in Sweden or the HSR Tours-Bordeaux in France (Stripple and Uppenberg, 2010; de Bortoli, Bouhaya and Feraille, 2020).

Furthermore, the purpose of studying rail transport from an environmental perspective can be used to develop Environmental Product Declarations[1] (Stripple and Uppenberg, 2010) or develop a calculation tool to compare carbon footprint of railway networks between several countries (Tuchschmid *et al.*, 2011). Rail transport can also be compared with other transport modes for passengers or freight: for example in the US (Chester, 2008; Chester and Horvath, 2009; Nahlik *et al.*, 2016), but also in Nigeria (Gujba, Mulugetta and Azapagic, 2013). Yet, comparing the environmental impacts of rail transport of passengers or goods with other transport modes is outside the scope of this thesis.

[1] Information about Environmental Product Declarations are available on the website of The International EPD® System (The International EPD® System, 2017).

2.2.2 Life cycle models

In this section the focus is placed on studies evaluating the impacts of rail transport systems from a life cycle perspective comprising at least railway infrastructure.

The aim and scope definition of the study provides a framework for the system boundaries considered and the methodology used to evaluate the environmental impacts.

Several tools may be used to calculate environmental impacts of the considered system. The most common among environmental impact studies of railway is life cycle assessment which can also be combined to economic input-output methodology to form a hybrid EIO-LCA as used to evaluate passenger transport in the US (Chester, 2008) or the carbon footprint of the Beijing-Shanghai high-speed railway (Lin *et al.*, 2019b).

It is challenging to determine exactly how long a railway infrastructure is going to last in the future. Often, a long period is considered (it can be up to 120 years (de Bortoli, Bouhaya and Feraille, 2020)) and is determined based on the lifetime of components (Stripple and Uppenberg, 2010).

The period of calculation is long, and it may seem surprising to try to estimate what is going to happen in several decades. However, as mentioned by Stripple and Uppenberg (2010), the purpose of considering a long period of calculation is to have a global overview over the various life stages and assess how large their contribution is to the environmental impacts over the entire lifetime of the system considered.

All activities related to the system boundaries considered and occurring during the calculation period have to be included. Saxe *et al.* (2016) emphasizes that any activity related to the construction of rail infrastructure has an impact and those activities should be precisely recorded. This is also applicable for any activity related to rail transport to perform a comprehensive environmental impact assessment.

Data collected may come from a large panel of sources, both primary sources and secondary sources: experts (e.g. Deutsche Bahn AG in Germany (von Rozycki, Koeser and Schwarz, 2003; Schmied and Mottschall, 2013)), railway line concessionaire (e.g. in France (de Bortoli, Bouhaya and Feraille, 2020)), government (e.g. Chinese Ministry of Railways (Yue *et al.*, 2015; Wang *et al.*, 2016), life cycle inventory databases (e.g. Ecoinvent (Wernet *et al.*, 2016)), and literature through the use of previously published research. However, data collection is identified as a challenging task and linearity assumptions are used to overcome this issue (Olugbenga, Kalyviotis and Saxe, 2019). Therefore, actors responsible for building and operating railway lines are encouraged to communicate project-specific data (Olugbenga, Kalyviotis and Saxe, 2019).

Unsurprisingly, data availability influences which life cycle stages and activities to consider in the impact assessment. The HSR study in China only includes the construction phase of the infrastructure (Yue *et al.*, 2015). The literature review performed by Olugbenga, Kalyviotis and Saxe (2019) indicates that disposal stage is only included in a handful of studies. The exclusion of end of life stage is also globally observed in LCA studies of transport infrastructure (Saxe and Kasraian, 2020).

2.3 Main findings from environmental studies of railway

In this section, main findings regarding environmental impacts from railway studies are described.

2.3.1 Rail infrastructure

Rail transport infrastructure is constructed depending on local conditions, especially regarding the preparation of the construction site (deforestation, earthworks) and the length of bridges or tunnels.

In the environmental assessment of the Bothnia Line, Stripple and Uppenberg (2010) assumed that forest was present almost all over the railway area and estimated that, with this assumption, deforestation is responsible for nearly 20% of global warming impact of the railway line.

Raw material production has a large contribution to environmental impact from the construction phase when compared with their transport and the operation of machinery used for the construction. Chang and Kendall (2011) estimated that material production was responsible for about 80% of the CO_2-eq emissions resulting from the construction of the California's HSR infrastructure. Two raw materials are identified as having a larger contribution to global warming than others: cement and steel. Stripple and Uppenberg (2010) estimated that cement and steel were responsible for about 85% of the global warming potential from infrastructure material required in the Bothnia line. In addition, the main contribution of steel comes from steel used in the tracks, and mainly from rails production (Stripple and Uppenberg, 2010). Environmental impact results disaggregated into railway components and subcomponents from the Tours-Bordeaux HSR also indicate that rails have the largest contribution to several impact categories such as ecotoxicities (terrestrial, marine, and freshwater) and human toxicity (de Bortoli, Bouhaya and Feraille, 2020). Moreover, rails are also the second contributor to climate change after the roadbed (de Bortoli, Bouhaya and Feraille, 2020). Rails are therefore important elements to study. Their lifetime can be very short in case of high load occupation of the line coupled with extreme weather conditions such as for the Mumbai suburban railway where rails are considered to last about 10 years (Shinde *et al.*, 2018).

Since bridges and tunnels require extensive quantities of steel and cement (Wang *et al.*, 2016), construction of these structures influence resource consumption and environmental impacts of the railway line (von Rozycki, Koeser and Schwarz, 2003; Chang and Kendall, 2011; Yue *et al.*, 2015). A generalized model of infrastructure embodied GHG emissions, attempting to evaluate how increasing the length of tunnels or elevated sections increases GHG emissions, supports this finding (Olugbenga, Kalyviotis and Saxe, 2019).

When it comes to compare the contribution of the different life cycle stages of the railway infrastructure to the environmental impact, different patterns can be observed and are dependent on the activities included for each life cycle stage. On the first hand, regarding the Bothnia Line, the global warming from the maintenance of the infrastructure represents about 36% of the impact of its construction (Stripple and Uppenberg, 2010). On the other hand, the maintenance phase of the Tours-Bordeaux infrastructure seems to represents about 80% of the construction impact (de Bortoli, Bouhaya and Feraille, 2020). Moreover, the choice of end-of-life allocation grants credits for recycling and therefore presents negative impact values (considered as positive impacts) which reduces the life cycle environmental impacts of the railway line (de Bortoli, Bouhaya and Feraille, 2020).

2.3.2 Operational energy use

When the energy consumption of a rail transport system is studied and the operation of rail vehicles is included, this process is the most energy consuming (von Rozycki, Koeser and Schwarz, 2003; Stripple and Uppenberg, 2010). The type of fuel (electricity/diesel) is therefore an important factor when it comes to the environmental impacts from this energy consumption.

The study of Belgian rail freight transport evaluates the impacts of both diesel and electric trains (Merchan, Belboom and Léonard, 2020). Main differences come from the location of the emissions and affected environmental impacts: for diesel trains, direct exhaust emissions from combustion have a great contribution to climate change, photochemical ozone formation, acidification, and terrestrial eutrophication, while indirect emissions from electricity production to power electric trains contribute greatly to climate change, ozone depletion, and ionizing radiation (mainly because of nuclear power).

Merchan, Belboom and Léonard (2020) indicate that a higher efficiency is observed for electric trains and environmental impacts from electricity can be decreased by changing the supply mix. This recommendation is also supported by Yue *et al.*(2015) whose study highlights the environmental impacts of coal-based electricity produced to power high-speed rail in China. In Sweden, where the electricity is mainly produced from hydropower, the operation of rail vehicles on the Bothnia Line represents less than 1% of global warming impact (Stripple and Uppenberg, 2010).

Environmental impacts from operation are also dependent on the amount energy required to run the vehicles. For example, tunnels increase the energy consumption (Pritchard and Preston, 2018). Therefore, decisions taken at the design and construction stages of the infrastructure also influence the operational energy consumption of the rolling stock.

2.4 Overview

Studies regarding environmental impacts of railway are diverse and analyse rail transport from several perspectives.

Table 2.1 provides a summary of the studies included in this literature review evaluating environmental impacts of railway. Based on this table, one may observe that high-speed rail studies are the most common type of studies retrieved in this literature review. However, these studies still provide useful insights about environmental impacts of railway in general.

Moreover, one may also notice that one environmental assessment was found for Africa, a study comparing passenger transport and estimating future scenarios in Nigeria (Gujba, Mulugetta and Azapagic, 2013). However, this study does not develop a specific life cycle inventory for Nigeria rail transport, and uses life cycle inventory data from life cycle databases (Gujba, Mulugetta and Azapagic, 2013). Some other studies present environmental results regarding railway development in developing countries, India and China (Yue *et al.*, 2015; Shinde *et al.*, 2018; Lin *et al.*, 2019a). Nevertheless, railway development situation in China appears hardly comparable with current railway development in Africa. This thesis is therefore contributing to filling the knowledge gap regarding life cycle assessment of rail transport in Africa by choosing to study an African railway line under construction.

Table 2.1 –Overview of environmental assessments of railway included in the literature review

Authors, year	Line/system (Country)	Rail type	Description	Boundaries		
				Infrastructure	Rolling stock	Operation
(von Rozycki, Koeser and Schwarz, 2003)	Hannover-Wuerzburg (Germany)	HSR	325 km Double-track	C, M	C, M	I, RS
(Spielmann *et al.*, 2007)*	Switzerland, Europe, China, US	HSR, long-distance, regional	/	C, M, EoL	C, M, EoL	I, RS
(Chester, 2008), (Chester and Horvath, 2009)	US	Several (including HSR)	/	C, M	C, M	I, RS
(Stripple and Uppenberg, 2010)	Bothnia Line (Sweden)	Long-distance	209 km Single-track (with side tracks)	C, M	C, M,	I, RS
(Åkerman, 2011)	Europabanan (Sweden)	HSR	740 km Double-track Proposed	C, M	C, M	I, RS
(Grossrieder, 2011)	Trondheim-Oslo (Norway)	HSR	486 km Double & single-track Proposed	C, M, EoL	C, M, EoL	I, RS
(Chang and Kendall, 2011)	San Francisco-Anaheim (California, US)	HSR	725 km Double-track** Proposed	C	/	/
(Tuchschmid *et al.*, 2011)	Several	Several	/	C, M	C, M	I, RS
(Schmied and Mottschall, 2013)	Germany	Several	/	C, M	C, M	I, RS
(Gujba, Mulugetta and Azapagic, 2013)	Nigeria	/	1.13 billion pkm/yr (+scenarios)	C	C	RS
(Yue *et al.*, 2015)	Beijing-Shanghai (China)	HSR	1318 km	C	C, M, EoL	RS
(Nahlik *et al.*, 2016)	California (US)	/	8500 km	C, M	C, M	I***, RS
(Shinde *et al.*, 2018)	Mumbai (India)	Suburban	983.8 km existing +236.9 km proposed (total track length)	C, M	C, M	I, RS
(Lin *et al.*, 2019b)	Beijing-Shanghai (China)	HSR	1318 km	C, M	C, M	I, RS
(de Bortoli, Bouhaya and Feraille, 2020)	Tours-Bordeaux (France)	HSR	340 km Double-track	C, M, EoL	/	/
(Merchan, Belboom and Léonard, 2020)	Belgium	/	3248 km Double-track (calculated - 2012)	C, M, EoL	C, M, EoL	RS

C = construction, M =maintenance, EoL = end-of-life, I = infrastructure, RS = rolling stock
*This report is only the description of the life cycle inventory used in Ecoinvent database
**Seems to be a double-track railway line, but not explicitly stated in the study
***Mentioned as included in the system boundary, but only construction and maintenance specified in the paragraph about rail transport

3 Methods and materials

In the project conducted during the autumn semester (Rousseau, 2019), materials composition and energy requirements of various railway components were collected and a life cycle Assessment was performed on a fictive scenario. The purpose was to investigate the global warming impact of the different components in a rail transport system including the infrastructure, the rolling stock, and the operation (Rousseau, 2019).

As presented in the literature review, life cycle environmental impacts of railway, and transport in general in Africa are relatively unexplored in comparison to other geographic areas (Europe, Asia, and US). In this thesis, it has been decided to identify a railway line or a railway system in development in Africa to evaluate its environmental impacts by applying the life cycle assessment methodology. Life cycle assessment, the case study, and the model built to perform the life cycle assessment of the chosen case are therefore presented in this chapter.

3.1 Life cycle assessment methodology

Life cycle Assessment is an analytical tool used in the *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* (ISO, 2006b, p. 4).

The International Organization for Standardization, ISO14040:2006 and ISO14044:2006, provides the guidelines to perform an LCA (ISO, 2006a, 2006b). Four steps are implemented as shown in Figure 3.1: (1) Goal and scope definition, (2) Life cycle inventory, (3) Life cycle impact assessment and (4) Interpretation.

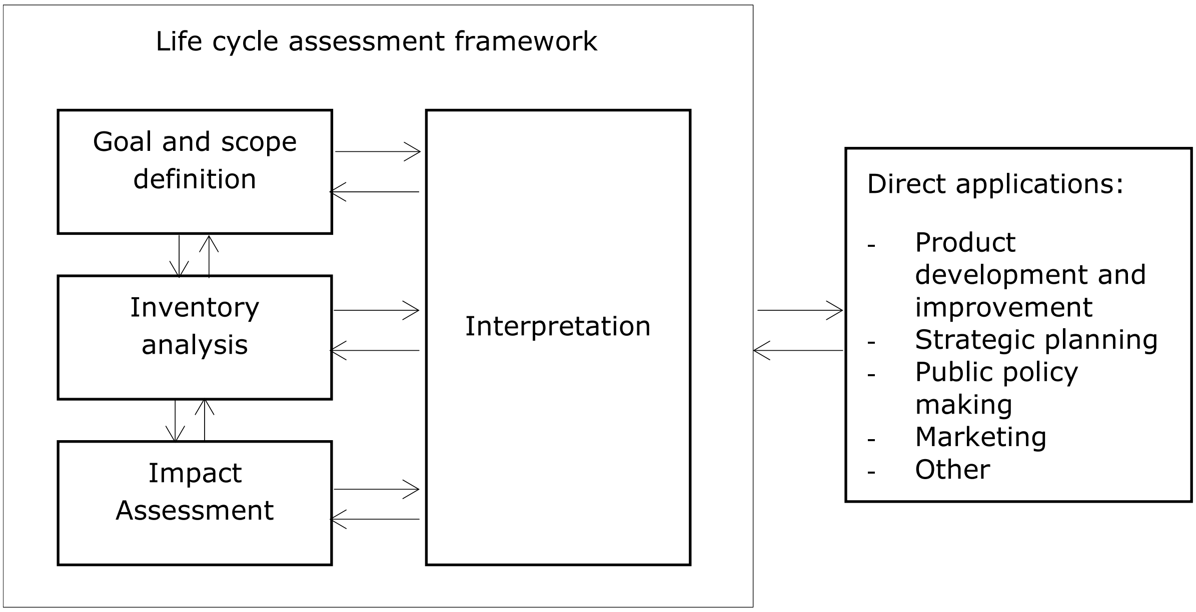

Figure 3.1 – Stages of life cycle assessment – Figure from (ISO, 2006b)

Each of the four stages is applied to the system being analysed throughout this thesis: (1) Goal and scope definition in section 3.3, (2) Life cycle inventory in Chapter 4, (3) Life cycle impact assessment in Chapter 5 for the baseline scenario and Chapter 6 for the development of alternative scenarios. (4) Interpretation is applied all along the LCA but it is detailed to a larger extent in Chapter 7 to review and discuss data collection from the inventory stage, environmental impacts calculated, and draw some conclusions.

3.2 Case description: The Standard Gauge Railway in Tanzania

In 2017, CO_2 emissions from fuel combustion in Tanzania were estimated to be about 10 million tonnes of CO_2 and road transport was responsible for about half of these emissions (IEA, 2019a). In Tanzania, this represents a rather low quantity of emissions per capita (about 90 kgCO_2/capita from road transport while the world average reaches almost 800 kgCO_2/capita in 2017) (IEA, 2019a). However, roads suffer from safety and overloading issues, and rail transport could have the potential to address these issues by transferring goods from road to rail and reducing the number of fatalities on the roads (AfDB, 2013).

3.2.1 Railway in Tanzania

Two railway networks exist in Tanzania: the old metre gauge railway (MGR) built at the beginning of the 20th century during colonial times and the TAZARA railway line built in the 1970s (AfDB, 2013). However, under-performance of their operations has been observed for both freight and passenger transport, especially for the MGR which experienced a large deterioration of its services (AfDB, 2013). To deal with this situation and stimulate rail activities in Tanzania, the Government has launched the construction of a new railway line: the Standard Gauge Railway[2] (SGR) which will be managed by the Tanzania Railways Corporation (TRC) (ERM, 2019).

3.2.2 The SGR: an overview

This railway line in development is the chosen object of study in this thesis and a model has been built, which is called the SGR-model.

The SGR is an electrified railway line of 1219 km, built closely to the MGR and designed for a maximum speed of 160 km/h carrying both passengers and freight (ERM, 2019).

This large-scale construction project is divided into 5 sections[3] (TRC, 2018):

- Section 1: Dar Es Salaam – Morogoro
- Section 2: Morogoro – Makutupora
- Section 3: Makutupora – Tabora
- Section 4: Tabora – Isaka
- Section 5: Isaka – Mwanza

The sections 1 and 2 are currently under construction. Yapı Merkezi and Mota Engil Africa are the contractors responsible for the construction of section 1, and the construction of section 2 is built by Yapı Merkezi (TRC, no date a). The route lengths are respectively of 205 and 336 km but the track lengths (which include main line and sidings) are of 300 km and 422 km (TRC, 2018). It is sometimes possible to read slightly different route length values, for example 202 km (Yapı Merkezi, 2018b) instead of 205 km for the section 1, but it has been decided to consider route lengths of 205 km and 336 km for

[2] Standard Gauge means that the distance between the inner parts of the rails is 1435 mm.

[3] In this thesis, the term "section" is used but in some other documents related to the SGR in Tanzania, the terms "lot" or "phases" are used ("lot" is especially used in the Environmental and Social Impact Assessment report (ERM, 2019)).

this study since these values are also reported in the Environmental and Social Impact Assessment (ESIA) report (ERM, 2019).

3.3 The SGR-model

To be able to perform an LCA of the SGR, data had to be collected and a model was built. All along this thesis, this model is referenced as the SGR-model. A distinction must be done between the SGR and the SGR-model since many modelling assumptions and estimates made in this thesis do not reflect the SGR reality.

3.3.1 Goal and scope

Before the construction of a new railway line in Africa, an environmental study is preliminarily completed such as for the Standard Gauge Railway line recently built in Kenya (Africa Waste and Environment Management Centre, 2012) and the Standard Gauge Railway line in Tanzania which is under construction (ERM, 2019). However, both studies do not include a complete environmental impact assessment following the life cycle environmental assessment methodology comprising all the life cycle stages of the railway lines.

The objectives of this thesis are therefore to contribute to railway life cycle environmental studies by evaluating the potential environmental impacts of the SGR-model and identify how the different processes and activities included in the SGR-model contribute to these environmental impacts.

The future function of the SGR is to transport passengers and freight between Dar Es Salaam and Mwanza. However, since only the first two sections (from Dar Es Salaam to Makutupora) are under construction and will be in operation in the near future, the functional unit for this environmental assessment comprises rail transport of passengers and freight along these two sections only. A 60-year period of calculation is chosen. Alternative functional units are also considered, 1 passenger-kilometre and 1 tonne-kilometre, for comparison of environmental impacts with some previous railway research.

The system boundaries of the system define which processes and life cycle stages are included in the environmental impact assessment (ISO, 2006a). A simplified flowchart of the SGR-model is depicted in Figure 3.2 and shows the three subsystems (infrastructure, rolling stock, operation) composing the SGR-model as well as the life cycle stages considered.

Each of the three foreground subsystems can be divided into several activities and processes requiring inputs of materials and energy. Details are provided in the Life cycle Inventory in Chapter 4.

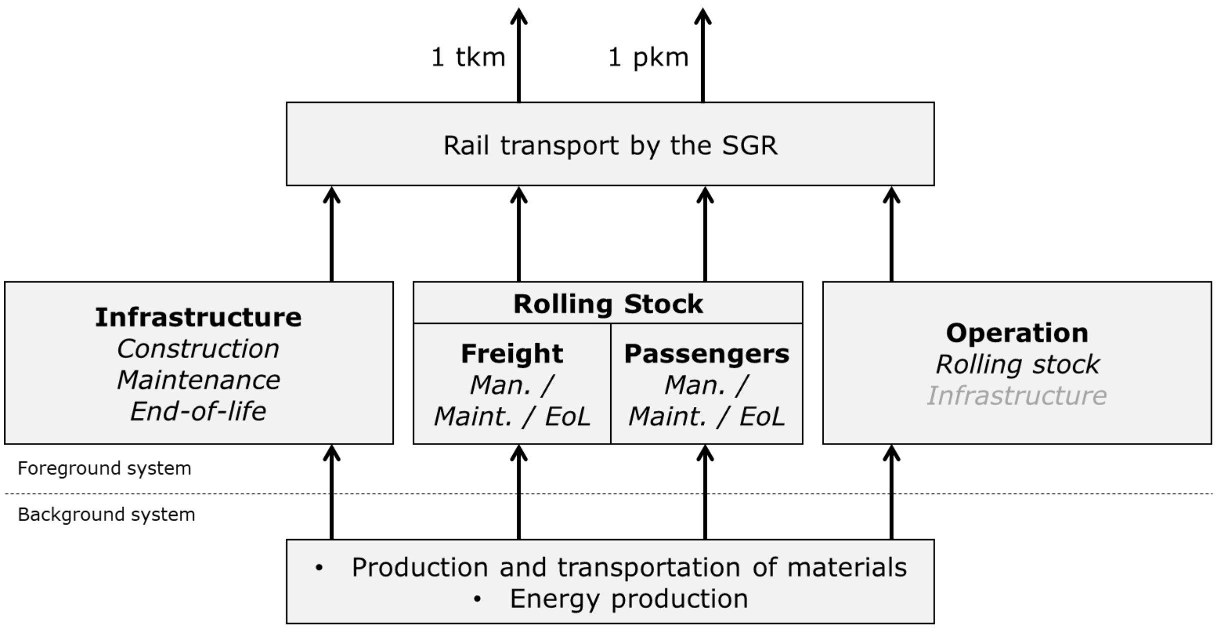

Figure 3.2 - Simplified flowchart of the SGR-model.
Man. = Manufacture / Maint. = Maintenance / EoL = End-of-life. Infrastructure in the box Operation is in light grey because this activity is excluded from the SGR-model.

3.3.2 Inventory analysis: data collection

After several e-mail exchanges with employees from Yapı Merkezi and attempts to contact the Tanzania Railways Corporation, the collection of specific project data did not succeed. Therefore, the life cycle inventory of materials and energy requirements for the SGR was built using available online sources of information.

The main source of information about the SGR is the Environmental and Social Impact Assessment (ESIA) report available on the website of Yapı Merkezi written by the consulting company Environmental Resources Management (ERM) (ERM, 2019).

Videos about the construction progress of the SGR are available on the YouTube channel of Yapı Merkezi Tanzania (Yapı Merkezi Tanzania, no date) and on the YouTube channel of the TRC (TRC RELI TV, no date). Watching online videos of the construction progress was valuable to see how the SGR looks like and understand how infrastructures are built even if this does not directly provide quantitative data.

Additional sources such as press releases or online websites have also provided useful information and are referenced when they are used.

When no specific data was available or when insufficient details were provided, data were collected from previous railway research, and assumptions and estimates were made.

3.3.3 LCA tools and impact assessment

Once the inventory of materials, energy, transport and direct environmental stressors such as emissions to air/soil/water is established for the foreground system, data for the background processes are retrieved from the Ecoinvent v3.2 database (Wernet *et al.*, 2016). In addition, Ecoinvent was also used for the foreground processes related to the rolling stock. The purpose of using a generic database such as Ecoinvent is to generate the life cycle inventory of elementary flows of resources and environmental stressors.

During the life cycle impact assessment (LCIA) stage, the elementary flows of resources and environmental stressors are converted into environmental impacts through classification and characterisation steps. Depending on their contribution to environmental damages, resources and emissions are assigned to environmental impact categories (classification). Then, for each impact category, factors of multiplication (characterisation factors) are applied to assigned resources and emissions to calculate impact results (characterisation). (Hauschild and Huijbregts, 2015)

The educational LCA software Arda is used for LCIA. Arda has been developed by the Industrial Ecology research group at NTNU. A Microsoft Excel template is filled with foreground processes and links them with background processes from Ecoinvent v3.2. MATLAB R2018a is used to perform the impact assessment calculations (classification and characterisation steps) by using the impact assessment method ReCiPe 2008 (Goedkoop *et al.*, 2013) version 1.11.

ReCiPe offers two levels of environmental impact categories: midpoint and endpoint levels. Midpoint impacts are calculated during the characterisation phase in LCIA. Table 3.1 presents the 18 midpoint impact categories available. Once the midpoint results are obtained, they can be grouped and multiplied with conversion factors to calculate impacts at the endpoint level (Goedkoop *et al.*, 2013). Three endpoint indicators can be calculated based on the midpoint results: Human health, Ecosystems, and Resources. Conversion factors from midpoint to endpoint are available in the Excel spreadsheet from the ReCiPe impact assessment method version 1.11 (Goedkoop *et al.*, 2013, 2014).

Based on these conversion factors, midpoint categories contributing significantly to the endpoint categories have been selected as environmental impact categories to include in this thesis:

- Contributors to Human Health: climate change, human toxicity, and particulate matter formation.
- Contributors to Ecosystems: terrestrial acidification, freshwater eutrophication, and natural land transformation. Ecotoxicities (terrestrial, freshwater, and marine ecotoxicities) are not included as main impact categories to study but are discussed when they present interesting results.
- Contributors to the endpoint Resources: fossil depletion and mineral resource depletion.

Moreover, ReCiPe allows calculations at midpoint and endpoint levels from three perspectives (individualist, hierarchist, egalitarian). The individualist perspective considers a short time horizon, the hierarchist perspective follows *"common policy principles"* and the egalitarian perspective is the *"most precautionary perspective"* by considering a long time horizon (Goedkoop *et al.*, 2013, p. 16). For this thesis, the hierarchist perspective is selected.

3.3.4 End-of-life management

End-of-life management in Arda uses the allocation cut-off by classification methodology from Ecoinvent. The same approach is adopted in the SGR-model to deal with end-of-life management of disposed railway components. The allocation cut-off by classification in Ecoinvent (no date a) assumes that the production of a component made from raw materials is allocated to the primary user (here the SGR infrastructure). In case of recycling, no credit is given to the primary user and the environmental impacts of a component made from recycled materials only come from the recycling processes (Ecoinvent, no date a).

Table 3.1 – Midpoint impact categories and their respective units and abbreviations (Goedkoop *et al.*, 2013) **– In bold are the selected impact categories for this thesis.**

Impact category	Unit	Abbreviation
Agricultural land occupation	m2a	ALO
Climate change	**kg CO2 eq**	**CC**
Fossil depletion	**kg oil eq**	**FD**
Freshwater ecotoxicity	kg 1,4-DB eq	FET
Freshwater eutrophication	**kg P eq**	**FE**
Human toxicity	**kg 1,4-DB eq**	**HT**
Ionising radiation	kg U235 eq	IR
Marine ecotoxicity	kg 1,4-DB eq	MET
Marine eutrophication	kg N eq	ME
Mineral resource depletion	**kg Fe eq**	**MRD**
Natural land transformation	**m2**	**NLT**
Ozone depletion	kg CFC-11 eq	OD
Particulate matter formation	**kg PM10 eq**	**PMF**
Photochemical oxidant formation	kg NMVOC	POF
Terrestrial acidification	**kg SO2 eq**	**TA**
Terrestrial ecotoxicity	kg 1,4-DB eq	TET
Urban land occupation	m2a	ULO
Water depletion	m3	WD

4 Life Cycle Inventory

This chapter is the development of the life cycle inventory of materials and energy for the SGR-model. Data collected as well as assumptions and estimates are described. The chapter is divided into several sections: rolling stock, operation, infrastructure construction, infrastructure maintenance, and infrastructure end-of-life.

4.1 Rolling stock

As the SGR is not operational yet, it is challenging to get a precise description of the rolling stock composition. A proposed rolling stock composition is indicated in the ESIA report comprising locomotives, electric multiple unit, passenger coaches, and freight wagons (ERM, 2019, p. 70). However, no description of their technical characteristics nor specific vehicles model names is provided. In addition, this proposed rolling stock composition is probably a first procurement of rail vehicles not reflecting the total amount of rail vehicles used over a 60-year period of calculation.

In the SGR-model, the rolling stock is therefore modelled in a simple way by collecting information about passengers and freight transport service from the ESIA report, by using datasets available in the Ecoinvent v3.2 database (Wernet *et al.*, 2016), and making additional assumptions.

4.1.1 Description

The ESIA report details a future scenario for freight and passenger transport: the total freight load and total passenger load to be transported is 12.9 million tons[4]/year and 1.1 million passengers/year by 2029 (ERM, 2019, p. 418). In addition, the report (ERM, 2019, p. 70) indicates that the service provided by the SGR consists of:

- 24 trips (20 for freight and 4 for passengers) for 300 days/year.
- 20 trips (16 for freight and 4 for passengers) for 65 days/year when routine maintenance is carried out.

The rolling stock composition in the SGR-model is estimated to satisfy the transport service described above. The approach to calculate the number of rail vehicles necessary over the 60-year period of calculation is similar to the one performed in the life cycle assessment of future high-speed rail in Norway (Grossrieder, 2011). The lifetime of rolling stock considered is the life performance in kilometres instead of years because rail vehicles can be used intensively and their lifetime in years decreases (MiSA AS, 2011).

4.1.2 Manufacture, maintenance and end-of-life

To estimate manufacturing, maintenance, and end-of-life emissions of the rail vehicles, datasets from the Ecoinvent v3.2 database (Wernet *et al.*, 2016) are considered. Several types of rail vehicles are available (high-speed, long-distance, and regional trains for passenger transport, locomotive and goods wagon for freight transport) and are modelled based on rail vehicles from Germany and Switzerland.

[4] In this thesis, it is assumed that "tons" refers to "metric tons" (or "tonnes")

4.1.2.1 Passenger trains

Passenger trains in the SGR-model are modelled on the long-distance rail vehicle dataset (Spielmann, no date e). A short description of this vehicle is available in Table 4.1.

Table 4.1 – Description of long-distance rail vehicle available in the Ecoinvent database

Type of rail vehicle	Description
Long-distance	The long-distance train is modelled based on the IC 2000, weighs about 317 t, and offers a maximum speed of 200 km/h. The vehicle is composed of a locomotive and 7 passenger carriages. About 1400 seats are available. Its total kilometric performance is 20,000,000 km. The disposal process is included in the production process.
Sources: (Spielmann, no date e; Spielmann *et al.*, 2007)	

To determine the number of passenger trains needed to satisfy the passengers transport demand, various constraints need to be considered:

- Period of calculation of 60 years.
- 4 trips per day (1460 trips per year).
- Trip length of 541 km.

The number of passenger trains needed is estimated using its lifetime performance in kilometres:

$$\frac{total\ km\ needed\ over\ 60\ years}{lifetime\ performance\ km/vehicle} = \frac{60 * 1460 * 541}{20\ 000\ 000} = 2.37$$

To provide rail passenger transport service over 60 years, at least 3 trains would be required, and additional trains could be necessary in case of maintenance. However, the environmental impacts of only 2.37 vehicles are included in the 60-year period calculation.

4.1.2.2 Freight trains

The ESIA report indicates that a freight train is composed of two locomotives and 63 goods wagons and that the gross weight of the wagons is 3693 t or 2792 t depending on the direction of the train – from Dar Es Salaam or to Dar Es Salaam (ERM, 2019, p. 420). Since the same number of trains are going in both directions, the average gross weight of the wagons is 3242.5 t. The freight load is 2283 t or 1382 t depending on the direction giving an average of 1832.5 t resulting in a tare weight for one wagon of 22.38 t.

Each freight train is modelled using the locomotive and the goods wagons available in the Ecoinvent v3.2 database (Wernet *et al.*, 2016). A short description of these two vehicles is available in Table 4.2.

Table 4.2 – Description of locomotive and goods wagon available in the Ecoinvent database

Type of rail vehicle	Description
Goods wagon	The good wagon is modelled based on 65% closed wagons and 35% tank wagons. The weight of one wagon is about 23.2 t*. Its total kilometric performance is 845,900 km. The disposal is not modelled in the Ecoinvent database.
Locomotive	The locomotive is modelled based on the "Re 460". Its total kilometric performance is 9,600,000 km. The weight of a locomotive is about 84 t. As for the long-distance train, the disposal is included in the production process.
Sources: (Spielmann, no date a), (Spielmann, no date b), (Spielmann *et al.*, 2007) *The wagon dataset will be slightly adjusted to fit an average weight of 22.38 t.	

To determine the number of locomotives and goods wagons needed to satisfy the freight transport demand, various additional constraints need to be considered:

- Period of calculation of 60 years.
- 20 trips per day for 300 days/year and 16 trips per day for 65 days/year (7040 trips per year).
- Trip length of 541 km.

The numbers of goods wagons and locomotives needed can be estimated using their lifetime kilometric performance:

$$\frac{total\ km\ needed\ over\ 60\ years}{lifetime\ km\ performance/wagon} = \frac{60 * 7040 * 541 * 63}{845{,}900} = 17{,}019.34$$

$$\frac{total\ km\ needed\ over\ 60\ years}{lifetime\ km\ performance/locomotive} = \frac{60 * 7040 * 541 * 2}{9{,}600{,}000} = 47.61$$

As for the passenger transport, to provide rail freight transport service over 60 years, at least 17,020 goods wagons and 48 locomotives are required, and additional vehicles could be necessary in case of maintenance. However, the environmental impacts of only 17,019.34 goods wagons and 47.61 locomotives are included in the 60-year period calculation.

4.1.3 Traffic density

To be able to estimate the frequency of maintenance activities (section 4.4.2), it is necessary to estimate the traffic tonnage in million gross tonnes (MGT). The traffic tonnage corresponds to the sum of the weight of the rail vehicles running on the tracks (passenger trains, freight locomotives, and goods wagons) and the weight of the passengers and goods transported. However, due to a lack of information, empty movements of trains (due to maintenance for example) are not considered.

4.1.3.1 Passenger transport

The weight of a passenger train is assumed to be the same as for the long-distance passenger train in Ecoinvent: 317 t (Spielmann *et al.*, 2007). The passengers load is of 1.1 million passengers per year and the mean passenger weight and his baggage is assumed to be of 80 kg (0.08 t). This results in the following passenger transport tonnage per year:

$$Passenger\ transport = 317 * 1460 + 1.1 * 10^6 * 0.08 = 5.5 * 10^5\ t/year = 0.55\ MGT/year$$

4.1.3.2 Freight transport

As mentioned in section 4.1.2.2 the average gross weight of the wagons for one freight train is 3242.5 t. There are two locomotives per freight and their weight is assumed to be the same as for the locomotive available in Ecoinvent: 84 t (Spielmann, no date b).This leads in the following freight transport tonnage per year:

$$Freight\ transport\ = (3242.5 + 2 * 84) * 7040 = 2.401 * 10^7\ t/year = 24.01\ MGT/year$$

4.1.3.3 Global traffic

The global traffic tonnage corresponds to the sum of passenger transport tonnage and the freight transport tonnage leading to a value of 24.56 MGT/year.

4.2 Operation

4.2.1 Energy consumption

Only energy consumption from vehicles operation is included in the SGR-model. It is assumed that all rail vehicles running on the SGR use electric power. Operation of the infrastructure such as rail switches or signalling system operations are excluded from the SGR-model due to a lack of data.

4.2.1.1 Passenger trains

In the ESIA report, passenger train energy consumption estimates are reported to be of 22.3 kWh/km from Dar Es Salaam to Makutupora and 18.3 kWh/km from Makutupora to Dar Es Salaam (ERM, 2019, p. 419). This difference probably comes from the grade of the railway line. As it is indicated that there are two trains in each direction (ERM, 2019, p. 419), an average value of 20.3 kWh/km is considered as the energy consumption of a passenger train.

4.2.1.2 Freight trains

In the ESIA, freight train energy consumptions estimates are reported to be of 85.2 kWh/km from Dar Es Salaam to Makutupora and 68.2 kWh/km from Makutupora to Dar Es Salaam (ERM, 2019, p. 420). As for passenger trains, this difference probably comes from the grade of the railway line. The freight load which is lower for the Makutupora to Dar Es Salaam trip (from inlands to the port) also potentially influences the energy consumption. It is also indicated that there are the same number of trains in each direction (ERM, 2019, p. 420), therefore an average value of 76.7 kWh/km is considered as the energy consumption of a freight train.

However, one limitation is that the energy consumption reported in the ESIA considers the energy consumption of the trains transporting passengers and freight. Additional energy consumption is needed for activities such as shunting (Spielmann *et al.*, 2007), but these activities are excluded from the SGR-model due to a lack of information.

4.2.1.3 Electricity mix in Tanzania

The dataset for high-voltage electricity supply in Tanzania available in the Ecoinvent database v3.2 includes electricity production from various sources (mainly natural gas, hydropower, oil, and a very low quantity of electricity, less than 0.5% of supply mix, from wood chips) as well as import of electricity, losses during transmission, the transmission network, and direct ozone and N_2O emissions to air (Treyer, no date c).

4.2.2 Direct emissions

Contrary to trains running on diesel, trains running on electricity do not have direct emissions from fuel consumption. However, there are two other types of direct emissions (Spielmann *et al.*, 2007; Merchan, Belboom and Léonard, 2020):

- Direct emissions to air because of sulphur hexafluoride (SF_6) from traction substations. A value of $4.4 * 10^{-8}$ kg/kWh of electricity is referenced in Ecoinvent (Spielmann *et al.*, 2007).
- Direct emissions of particulates to air and direct emissions of iron to soil because of the abrasion of overhead contact lines, brakes, wheels, and rails.
    - For passenger trains, data are collected from the Ecoinvent process for transport of passengers by the long-distance train in Switzerland (Spielmann, no date g). The same passenger train is considered in the SGR-model and it is assumed that emissions to air and soil due to abrasion are similar.
    - For freight trains, the Ecoinvent process for transport by electric freight train in Switzerland is used (Gindroz, no date a). However, this process also includes diesel consumption of shunting processes which are excluded from the SGR-model. Therefore, the quantities of particulates emitted to air are the sum of particulates from diesel exhaust and from abrasion. The quantity of diesel for shunting activities reported in the Ecoinvent process (Gindroz, no date a) as well as the exhaust emissions factors (Spielmann *et al.*, 2007, p. 104) are used to estimate the particulates emissions due to diesel energy consumption. These estimated quantities are subtracted from the total particulates emissions resulting in estimates for particulates emitted to air from abrasion.

Table 4.3 gathers the values of direct emissions to air and soil from train operations.

Table 4.3 – Direct emissions to air and soil from train operations

Direct emissions	Quantity	Unit	Source
Sulfur hexafluoride/air	4.40E-08	kg/kWh	(Spielmann, 2007)
Particulates, > 10 um/air	1.16E-05	kg/pkm	"transport, passenger train, long-distance/CH" (Spielmann, no date g)
Particulates, > 2.5 um, and < 10um/air	1.05E-05	kg/pkm	
Iron/soil	2.81E-05	kg/pkm	
Particulates, > 10 um/air	1.57E-05	kg/tkm	"transport, freight train, electricity/CH" (Gindroz, no date a), (Spielmann *et al.*, 2007, p. 104)
Particulates, > 2.5 um, and < 10um/air	6.82E-06	kg/tkm	
Iron/soil	1.78E-05	kg/tkm	

4.3 Infrastructure construction

The construction of the first section started in May 2017 while the construction of the second section started in February 2018 (TRC, 2018). Railway operations for the first section were expected to start in November 2019 (TRC, 2018) but as it is possible to see on the latest online videos, the construction of this section is still in progress (Yapı Merkezi Tanzania, 2020a, 2020c).

4.3.1 Construction activities included in the SGR-model

The construction of the SGR is divided into several activities (ERM, 2019, pp. 39–40):

- Preliminary activities including surveys and geotechnical studies, land acquisitions (for permanent and temporary used areas[5]) and other activities preparing the construction phase.
- Clearance of land and vegetation.
- Earthworks including cut and fill activities.
- Tunnels, culverts, and crossing structures works (including bridges, underpasses, overpasses, pedestrian, and animal passages).
- Track works (ballast, sleeper, and rail laying activities).
- Power, signalling and telecommunications systems.
- Construction of buildings (train stations, marshalling yards).

However, due to the challenges of data collection and the lack of available information, the SGR-model does not include all the processes listed above. The following activities are therefore included in the construction phase of the SGR-model:

- Land and vegetation clearance
- Earthworks
- Tunnels
- Crossing structures & Viaduct
- Culverts
- Tracks
- Power and signalling system

In addition, land transformation and land occupation are estimated. Some processes have been excluded from the SGR-model: preliminary activities, buildings (ERM, 2019, p. 33) as well as fences preventing animals and pedestrians to cross the line (ERM, 2019, p. 461), transportation of equipment/construction machinery, construction of temporary infrastructures such as camps for workers as well as workers' commuting trips. Except for excavated materials, treatment of wastes produced on the construction site or at workers' camps are excluded from the SGR-model.

As a reminder, a 60-year period of calculation is assumed. Except track components having a shorter lifetime and being replaced during the maintenance phase, all the other components are assumed to have a lifetime of 60 years. Therefore, all construction impacts are accounted in this 60-year period.

4.3.2 Land and vegetation clearance

Before building the track bed, land and vegetation must be cleared. These land use and land use changes (LULUC) are responsible for the release of carbon stored in vegetation and soil. In the SGR-model, the carbon emissions estimation is based on a description of land cover areas (Right-of-Way and facilities areas) available in the ESIA report (ERM, 2019, pp. 290–292) and an article estimating average carbon stock for various land cover types in Tanzania (Mauya *et al.*, 2019). Some assumptions are made to associate the land cover types given in the ESIA with land cover types considered in the article. For the land covers affected by the change of land use, their area and their carbon content,

[5] Examples of temporary used areas: camps for workers, precast yard, mix wet plants, batching plants, crusher plants.

the amount of CO_2 emissions can be calculated based on 1 kg of carbon produces 3.67 kg of CO_2 (mCO_2 (kg) = mC(kg)*44/12).

The estimated amount of emissions from land and vegetation clearance is of 203,326 tCO_2 as shown in Table 4.4. A detailed version of this table is available in appendix (Appendix B1).

Table 4.4 – CO_2 emissions from land and vegetation clearance

Land cover (Land cover associated)	Hectares (Lot 1 + Lot 2)	Carbon stock	CO_2 emissions	
		tC/Ha	tCO_2/Ha	Lot1 + Lot2 (tCO_2)
Cropland (Cultivated land: grain and herbaceous crops (50:50))	1,556	3.45	12.65	19,683
Grassland (Wooded grassland)	1,304	7.20	26.40	34,426
Shrubs cover areas (Bushland: open)	1,183	14.30	52.43	62,029
Trees cover areas (Overall for forest)	713	33.35	122.28	87,188
Total	4,756			203,326
Sources: (ERM, 2019, pp. 290–292; Mauya *et al.*, 2019)				

4.3.3 Earthworks

Local conditions such as the topography and the type of soil where the railway line is constructed define necessary earthwork activities to establish a stable base before laying the track (Profillidis, 2006, chap. 9).

The ESIA report provides a global description of earthworks for the SGR especially cut-and-fill activities (ERM, 2019, p. 40):

- Cutting activity: use of excavators and loaders for cut works and use of dump trucks to transport cut material which will either be further used as fill material or dumped in dumping areas.
- Filling activity: use of graders and rollers to spread and compact fill material (fill material is either material from cutting activity (cut material) or material extracted and transported from borrow areas).

Some sources of information provide quantitative values of excavation activities for sections 1 and 2 (TRC, 2018; Yapı Merkezi, 2018b, 2018c). These values are reported in Table 4.5.

Table 4.5 – Earthworks volume

Section	Main line length (m)	Earthworks (m^3)	Earthworks (m^3)	Earthworks (m^3/m main line)	Earthworks (m^3/m main line)
Section 1[a]	205,000	3.30E+07	2.82E+07	138	145
Section 1[b]		2.34E+07			
Section 2[c]	336,000	5.00E+07	5.00E+07	149	
Sources: [a] (Yapı Merkezi, 2018b), [b](TRC, 2018), [c](Yapı Merkezi, 2018c)					

Since two different values for earthworks have been reported for section 1, the average value is calculated. Then, values of earthworks per metre of main line are calculated and the weighted average value for both section 1 and 2 is estimated to be of 145 m^3/m main line.

Earthworks reported for other railway lines in Africa (the Standard Gauge Railway in Kenya (Mombasa-Nairobi), the Awash-Weldiya railway under construction in Ethiopia and the Djibouti-Addis Ababa railway) range between 53 m^3/main line and 254 m^3/main line. Details about these earthworks are provided in appendix (Appendix B2). Earthworks are dependent on local conditions, but the estimated value 145 m^3/main line fits in the range of values from other railway lines in Africa. It is therefore considered in the SGR-model that 145 m^3 of earthworks per m of main line is required.

However, cutting and filling volumes have not been reported and it is challenging to describe accurately earthwork activities. The volume of earthworks is then assumed to correspond to the volume of soil and rock which must be handled during the construction phase. Soil and rocks are excavated, moved, and processed. All these activities use heavy machinery and are responsible for diesel consumption. For that reason, the earthwork process in the SGR-model is modelled by "excavation, hydraulic digger, RoW" (Kellenberger, no date) from Ecoinvent for the whole volume of earthworks and half of this volume is transported over 10 km (as specified in section 4.3.9).

4.3.4 Tunnel works

The section 2 of the SGR goes through mountains and four tunnels are comprised in the project. The tunnels represent a total length of 2,620 m (Yapı Merkezi BIZ Digital Magazine, 2019).

Videos of the construction progress (TRC RELI TV, 2019, 2020) show that the tunnels are built by using the drill and blast method. This method is also used in Norwegian tunnelling (Jernbaneverket, 2016). The inventory of materials and energy required for tunnelling activities is therefore based on Norwegian reports and literature.

4.3.4.1 Tunnel excavated profile dimensions

Dimensions of the tunnels have been based on a screenshot of one of the tunnels' entrance from one online video (TRC RELI TV, 2019) showing the construction of this tunnel. Explanations are provided in appendix (Appendix B3). It is assumed that the four tunnels have the same profile dimensions.

Table 4.6 - Tunnel excavated profile dimensions

	Cross-section area (m^2)
Excavated profile (total)	78
Excavated profile (lower part using machinery)	27.8
Excavated profile (upper part using explosives)	50.2
Tunnel arc length	25

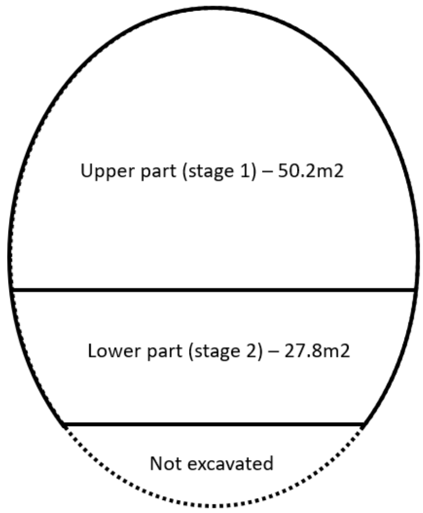

Figure 4.1 - Tunnel excavated profile

4.3.4.2 Excavation

The upper part of the tunnel is first excavated using explosives. The Follobanen model assumes a quantity of explosives of 1.7 kg/m^3 (Asplan Viak AS, 2011). It is assumed that the quantity of explosives for the tunnels in the SGR-model is similar.

The lower part of the tunnel is excavated later after securing the first part excavated and a hydraulic breaker (hydraulic hammer) is used. However, in Ecoinvent this machine will be represented by the process "excavation, hydraulic digger, RoW" (Kellenberger, no date).

4.3.4.3 Grouting

Before or after the use of explosives, injection of grout materials may be used to fill and seal the natural cracks and prevent water leakages (Jernbaneverket, 2016). Two types of grout materials are used in the Follobanen tunnel model: 1800 kg of cement and 100 kg of epoxy per tunnel metre (Asplan Viak AS, 2011). In this tunnel model, it is assumed that only cement is used for grouting.

The Follobanen tunnel has an excavated profile of 70 m^2 while tunnels for the SGR have a profile of 78 m^2. Cement injection quantity is therefore adapted for a profile of 78 m^2.

4.3.4.4 Securing

Based on observations of the video (TRC RELI TV, 2019), walls of the tunnel are secured by using lattice girders, shotcrete and steel bolts.

Lattice girders used in the tunnel construction consist of four bars forming a rectangular section attached together by sinusoidal side bars and cross bars. For this reinforced steel system, a weight of 20 kg per metre of lattice girder can be considered (COWI and Multiconsult, 2018, p. 34). This value seems to be reasonable when compared to the weight of similar 4-Bar lattice girders available in the market (DSI Tunneling LLC, 2018). A distance of 140 cm between two arches has been estimated based on a screenshot of a worker on a ladder between two arches from the video (TRC RELI TV, 2019). Details are provided in appendix (Appendix B4).

The lattice girders are then covered with shotcrete. Based on the Q-method[6], lattice girders may be used in the case of extremely poor rock quality and for such rock quality, shotcrete thickness is between 150-250 mm (Statens Vegvesen, 2020b, p. 38). A thickness of 200 mm shotcrete is chosen for this tunnel.

In addition to lattice girders and shotcrete, about 9 or 10 steel bolts seem to be placed between 2 steel arches (TRC RELI TV, 2019). Each bolt is assumed to have a weight of 16 kg (Asplan Viak AS, 2011).

4.3.4.5 Water protection and cast-in concrete

Another video of the tunnel construction progress (TRC RELI TV, 2020) leads to assume that a cast-in place concrete with membrane method is applied to build the surface of the tunnel and the water protection. Based on the Norwegian tunnelling guidebooks (Bruvik, 2012, p. 18; Statens Vegvesen, 2020a, p. 100), the cast-in concrete for water and frost protection with membrane[7] consists of three additional layers on top of the securing layer:

- A smoothing layer of shotcrete (typical thickness of 200 mm).
- A membrane and a non-woven geotextile (the membrane is a polymeric geosynthetic barrier of 2 mm minimum thickness (Statens Vegvesen, 2020b, pp. 41–43)).
- A layer of plain concrete (typical thickness of 400 mm).

In the tunnel model, a smoothing layer of concrete of 200 mm, a membrane of PVC of 2 mm and a layer of reinforced concrete of 400 mm instead of plain concrete are considered. Indeed, the video shows that a reinforced steel frame is placed against the membrane and then, concrete is poured thanks to a tunnel formwork.

In the Follobanen tunnel model, concrete elements were used to form the tunnel surface and they include 2% of reinforced steel (Asplan Viak AS, 2011). In the tunnel modelled for the SGR, it is assumed that reinforced steel also represents 2% of the reinforced concrete layer.

4.3.4.6 Support ground

The same video of the tunnel construction progress (TRC RELI TV, 2020) shows that concrete has been poured to form the tunnel floor. Tracks will probably be laid directly on this concrete part.

In this tunnel model, it is assumed that the floor is made of reinforced concrete with the same characteristics as the concrete wall (400 mm thickness and 2% of reinforced steel). The ground is 7.02 m wide based on the estimations in the appendix. However, since the bottom part of the tunnel is not rectangular, and the ground is probably not flat due to rocks, additional 5% of volume is added to an initial volume of 7.02 m*40 cm*length of the tunnel.

4.3.4.7 Electricity use

During the construction phase, electricity is consumed for various activities such as the ventilation system, lights, and other equipment. In this tunnel model, the electricity

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[6] The Q-method is a classification of rock mass quality and can be used to identify the type of rock support required in underground excavations (Norwegian Geotechnical Institute, 2015).
[7] «Kontaktstøpt vann- og frostsikringshvelv med membran»

consumption is assumed to be the same as for the Follobanen project in which a value of 3000 kWh per metre of tunnel is considered (Asplan Viak AS, 2011).

4.3.4.8 Diesel use

For this tunnel model, only the diesel uses for loading of rocks is taken into account and is assumed to be similar to the Follobanen project corresponding to a consumption of 54 L/m of tunnel (Asplan Viak AS, 2011).

4.3.5 Crossing structures & viaduct

In this activity, viaduct, bridges, overpasses, underpasses, cattle, and pedestrian underpasses are included. All these types of structures except viaduct are grouped under the name crossing structures in the SGR-model.

Many structures are considered as crossing structures and it is not possible to provide as many details in the inventory of materials and energy as for the tunnel construction. Material quantities (concrete, steel) and the amount of excavated materials are taken from railway concrete bridges and viaducts in Germany (Schmied and Mottschall, 2013, pp. 37–40). Concrete bridges and viaducts in the German study are double-track, however Mottschall and Schmied (2013) mention that single-track railway bridges emissions can be calculated as 60% of double-track railway bridges emissions. Therefore, in the SGR-model, the inventory of materials and energy for crossing structures and viaduct is estimated as 60% of the inventory from the German study. The inventory considered is described in Table 4.7.

Table 4.7 – Inventory of materials and energy for crossing structures in the SGR model

Material	Concrete bridges		Viaducts	
	Double-track	Single-track	Double-track	Single-track
Concrete (m^3/m)	14	8.4	32	19.2
Steel (ton/m) (15% structural steel and 85% reinforced steel)	1.5	0.9	3.5	2.1
Excavated materials (m^3/m)	5.2	3.12	26	15.6
Source: double-track inventory (Schmied and Mottschall, 2013), single-track calculated as 60% of double-track requirements				

Information reported regarding the location of crossing structures differ between the ESIA report (ERM, 2019, pp. 27–32) and information reported online such as in the videos published on the YouTube channel of Yapı Merkezi Tanzania (Yapı Merkezi Tanzania, no date). This is not surprising considering that the information reported in the ESIA report are proposed crossing structures and that changes may occur during the actual construction stage.

The ESIA report mentions that viaducts are proposed to be built in the city of Dar Es Salaam (ERM, 2019, p. 27), this information is confirmed on the TRC website mentioning that a viaduct of 2.56 km is built in Dar Es Salaam (TRC, no date b).

The total length of crossing structures (excluding viaduct which has a length of 2.56 km) is the average of the minimum and maximum length of reported values from various sources. Table 4.8 summarizes values that can be found regarding crossing structures length and gives the total crossing structures length considered in the SGR-model.

Table 4.8 – Crossing structures length

Section	Description	Crossing structures (m)	Average crossing structures (m)	Total crossing structures (m)
Section 1[a]	Bridges and overpasses total length	3940*	3565	7937
Section 1[b]	Sum of bridges, overpasses, and underpasses lengths	3190		
Section 2[c]	Sum of bridges, overpasses, underpasses, and pedestrian & animal crossings lengths	4859	4372	
Section 2[b]	Sum of bridges, overpasses, and underpasses lengths	3886		
Sources: [a](Yapı Merkezi, 2018b), [b](ERM, 2019, pp. 27–32), [c](Yapı Merkezi, 2018c) *corresponds to the value reported 6500 m which is assumed to include the viaduct				

In the Bothnia Line study, road bridges, which have the same function as overpasses, are not included in the environmental impact of the railway line (Stripple and Uppenberg, 2010). However, in the SGR-model, it has been decided to consider overpasses as part of the railway infrastructure and its environmental impacts. Indeed, the SGR crosses major roads and its construction is responsible for construction needs in the road infrastructure. Since railway tracks are not laid upon overpasses, the length of overpasses needs to be considered to further establish the distinction of environmental impacts between open sections, crossings structures sections (without overpasses) and tunnels sections. Overpasses impacts will be allocated to the open sections impact. Table 4.9 shows the length of overpasses in the SGR-model.

Table 4.9 – Overpasses length

Section	Overpasses (m)	Total overpasses (m)
Section 1	768	1917
Section 2	1149	

Overpasses length for section 1 has been calculated using the proportion of overpasses length reported in the ESIA report (ERM, 2019, pp. 27–32) which is of 21.54% applied to the average length for section 1 (3940 m) resulting in 768 m. Overpasses length for section 2 has been calculated as the average reported values for overpasses by the ESIA report and Yapı Merkezi (1155.4 m (ERM, 2019, pp. 27–32) and 1142 m (Yapı Merkezi, 2018c)) resulting in 1149 m. The total length of overpasses is then 1917 m.

4.3.6 Culvert works

Culverts have the purpose to allow water to flow beneath the SGR embankment. There are several types of culverts of different width, height, and length. In the SGR-model, all culverts are modelled according to a simple design.

Culverts are assumed to be single cell box culverts made of reinforced concrete. A typical culvert design is referenced in the ESIA report (ERM, 2019, p. 37) but the document is not fully readable. However, a few information can be still be collected from this general layout. The size of the typical culvert is 1.5 m*1.5 m. It is assumed that these dimensions correspond to the inside dimensions of the culvert. In addition, by doing some simple measurements on the typical cross section drawing, the thickness of the concrete, and thus the volume, can be estimated. Figure 4.2 shows the estimated dimensions for a typical culvert in the SGR-model.

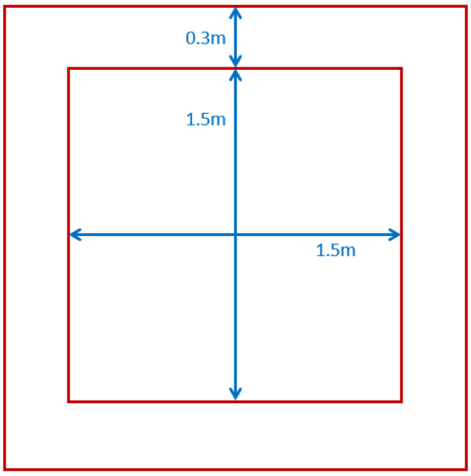

Figure 4.2 – Culvert cross section

Based on these dimensions, the volume of reinforced concrete is estimated to 2.16 m^3. The ratio steel (m^3)/concrete (m^3) is assumed to be the same as for crossing structures (concrete bridges) resulting in a steel quantity of 228 kg/m of culvert and a concrete volume of 2.13 m^3/m of culvert.

Table 4.10 shows the number of culverts in the SGR-model.

Table 4.10 – Number of culverts

Section	Culverts (nb)	Total culverts (nb)
Section 1[a]	460	960
Section 2[b]	500	
Sources: [a](Yapı Merkezi, 2018b), [b](Yapı Merkezi, 2018c)		

The average culvert length has been estimated from other railway lines and results in approximately 33.75 m per culvert (details are provided in appendix (Appendix B5)) giving a total length of 32,397 m.

The value of 33.75 m per culvert is close to the average length of an underpass from the ESIA report which is of 33.4 m (ERM, 2019, pp. 27–32). Therefore, considering a value of 33.75 m per culvert is reasonable.

4.3.7 Track works

The SGR is a ballasted track system and is composed of ballast, sleepers, rails, fastenings, and pads. The length considered is 722 km, corresponding to the track length comprising both the main line and sidings. The track composition is assumed to be the same all along the railway line.

The inventory of materials and energy for the track as well as the choice of Ecoinvent processes are based on the inventory of track components from the life cycle model of the Tours-Bordeaux railway in France (de Bortoli, Bouhaya and Feraille, 2020). This inventory is slightly modified according to the information provided in the ESIA report (ERM, 2019, pp. 24–25), and machinery consumption from the environmental life cycle assessment of track beds in the United Kingdom (Kiani, Parry and Ceney, 2008).

4.3.7.1 Ballast

In the SGR-model, ballast is made of crushed gravel and its quantity is estimated from the ballast volume of 2.5 m^3/m track (ERM, 2019, pp. 24–25) and a density of 1620 kg/m^3 (Stripple and Uppenberg, 2010).

4.3.7.2 Sleepers

The ESIA report specifies that sleepers are pre-stressed mono-block concrete sleepers weighing 280 kg and spaced 600 mm apart on the track (ERM, 2019, pp. 24–25).

Concrete sleepers are made of steel and concrete. To determine the quantity of steel, the proportion of steel in sleepers from the life cycle inventory of sleepers of the Tours-Bordeaux railway in France (de Bortoli, Bouhaya and Feraille, 2020) is considered: 3.44% of the sleeper weight (concrete (kg)+ steel (kg)). This results in a steel quantity of 9.63 kg and a concrete volume of about 0.11 m^3 per sleeper[8].

In addition, electricity is consumed for the manufacturing of sleepers and the consumed quantity is adapted from the life cycle inventory of sleepers of the Tours-Bordeaux railway in France (de Bortoli, Bouhaya and Feraille, 2020) resulting in a value of 3.23 kWh per sleeper.

4.3.7.3 Rails

The ESIA report specifies that rails are of type 60UIC and are continuously welded (ERM, 2019, pp. 24–25). This type of rail weighs 60.21 kg per metre of rail (ArcelorMittal, no date).

The welding arc process ($5 * 10^{-6}\ m/m$) is assumed to be the same as the one specified in the life cycle inventory of rails of the Tours-Bordeaux railway in France (de Bortoli, Bouhaya and Feraille, 2020).

In the SGR-model, the rail process does not consider switches and crossing which allow rail vehicle to change of track. However, if they were considered they would increase the amount of steel.

4.3.7.4 Fastenings and pads

Material composition of fastenings and pads is directly taken from the life cycle inventory of tracks of the Tours-Bordeaux railway in France (de Bortoli, Bouhaya and Feraille, 2020): 0.6 kg of steel per fastening and 0.4 kg of rubber per pad. Moreover, there are four fastenings and two pads per sleeper.

4.3.7.5 Diesel consumption

The use of machinery to spread the ballast and lay the sleepers and rails is responsible for consumption of diesel. In the SGR-model, this energy consumption is estimated from the environmental life cycle assessment of track beds in the United Kingdom (Kiani, Parry and Ceney, 2008). The energy consumption from machinery in the life cycle inventory of tracks of the Tours-Bordeaux railway in France (de Bortoli, Bouhaya and Feraille, 2020) is not considered in the SGR-model since train machine unit was used for the construction of the Tours-Bordeaux railway line which seems rather unlikely for the construction of the SGR. The ESIA report mentions that concrete sleepers are laid by using sleeper attachment on excavators (ERM, 2019, p. 40) and online videos show that several machines are used. The progress video from July 2019 (Yapı Merkezi Tanzania,

[8] Concrete density considered is the density for "concrete, high exacting requirement" of 2420 kg/m^3 (Werner, no date a).

2019) shows an example of ballast spreading at 4min03 and an example of sleepers laying at 7min28.

Table 4.11 presents energy consumption from machinery used in track construction and maintenance (Kiani, Parry and Ceney, 2008).

Table 4.11 – Machinery used in track construction and maintenance

Machinery	Construction speed (h/km)	Diesel fuel consumption (l/h)	Consumption (l/km)	Consumption (MJ/m)
Rail laying machine	37	5	185	6.66
Sleeper laying machine	14	5	70	2.52
Ballast spreading machine	12	10	120	4.32
Tamping machine	32	15	480	17.28
Ballast cleaning machine	17	15	255	9.18
Ballast changing machine	17	15	255	9.18
Source: (Kiani, Parry and Ceney, 2008)				

In Kiani, Parry and Ceney (2008), only rail laying machine, sleeper laying machine, and ballast spreading machine are reported to be used during the construction stage. However, in the SGR-model, it is chosen to add the use of tamping machine at the construction stage. Based on a personal communication, tamping machine is used to adjust the track geometry after ballast spreading in a new track construction (AH Løhren 2020, personal communication, 8 May)[9].

4.3.8 Catenary works and signalling & telecommunication works

It is assumed that the same catenary works and signalling & telecommunication works are placed all along the tracks (main line and sidings). This approach was considered in the Bothnia Line study in which the length of electric power and control system is the same as the track length with sidings (Stripple and Uppenberg, 2010, p. 134).

The ESIA report mentions some catenary and signalling & telecommunication works (ERM, 2019, pp. 40, 42, 71).

- Catenary poles installation.
- Trenches in which pipes are installed and underground cables placed within.
- Mobile communication towers and other parts of telecommunication systems.
- Substations and Auto Transformers for power supply.

Nevertheless, since no quantitative information is provided, catenary and signalling & telecommunication system of the SGR is assumed to be equivalent to the life cycle inventory for power supply and signalling system of the Tours-Bordeaux railway in France (de Bortoli, Bouhaya and Feraille, 2020) even if the Tours-Bordeaux railway is a high speed line.

The six components included in the power supply and signalling system are trenches, catenary cables, catenary poles, connecting cables, energy boxes, and signs. However,

[9] Alf Helge Løhren is a Civil Engineer, PhD working at Bane NOR, the Norwegian Railway Infrastructure Manager

quantities of materials and energy need to be adapted for the SGR-model as the Tours-Bordeaux railway line is double-track while the SGR is single-track.

Material and energy quantities required for some components could be simply divided by two from a double-track to a single-track, but for some others a division by two does not seem applicable. In the German railway study, Mottschall and Schmied (2013) consider that the emissions of single-track components correspond to 60% of emissions of double-track components while some other single-track components correspond to 50% of double-track components (Schmied and Mottschall, 2013):

- Cable channel, signalling cable and signals: 60%
- Overhead lines: 50%

Therefore, the life cycle inventory for power supply and signalling system of the Tours-Bordeaux railway in France (de Bortoli, Bouhaya and Feraille, 2020) is adapted in the following way:

- Trenches, connecting cables and signs: 60%
- Catenary cables and catenary poles: 50%
- Energy boxes: 100%

There is no description of what exactly energy boxes are, but since they are entirely made of steel, it is assumed they correspond to technical rooms for power supply and there is the same quantity along the track whether it is a single or a double-track. In addition, two changes have been made in the life cycle inventory from de Bortoli, Bouhaya and Feraille (2020). Bronze has been added with the same quantity as the process "contouring, bronze" (which does not include bronze material (Classen *et al.*, 2009)). "Concrete blocks" in the process signs have been changed to "concrete, high exacting requirements" due to a lack of information regarding the density of concrete blocks used in this inventory.

4.3.9 Transportation of materials

Transport distances of materials are presented in Table 4.12. Calculations of transport distance are detailed in appendix (Appendix B6). Two transport datasets from Ecoinvent have been used: a transport market at the global scale for transport by lorry (Ecoinvent, no date b) since no information was available regarding the type of vehicles used to transport materials and a global shipping activity for maritime imports (Spielmann, no date f). The two transport datasets include fuel consumption as well as vehicles and infrastructure needed.

Table 4.12 – Assumptions regarding transport of materials and the associated railway components

Materials	Distance (km)	Associated railway components
Excavated material	10	Earthworks, tunnels, crossing structures & viaduct
Ballast	162	Track
Sleepers (from factory)	76	Track
Rail (& fastenings & pads) - Import	13,000	Track
Rail (& fastenings & pads) - From Dar Es Salaam port	270.5	Track
Concrete (& cement)	30	PSS, tunnels, crossing structures & viaduct, culverts
Metals (steel, bronze, copper, aluminium) - Import	9000	Track (steel for sleepers), PSS, crossing structures & viaduct, culverts, steel for tunnels
Metals (steel, bronze, copper, aluminium) - From Dar Es Salaam port	270.5	Track (steel for sleepers), PSS, crossing structures & viaduct, culverts
Metals (steel for tunnels) - From Dar Es Salaam port	282	Steel for tunnels

4.3.10 Land transformation and occupation

Building and operating a new railway infrastructure leads to transformation and occupation of land. The Ecoinvent process "railway track construction" (Spielmann, no date d; Spielmann *et al.*, 2007) includes environmental stressors related to these transformation and occupation. However, the respective inventory for these stressors is not reused in the SGR-model since these values are specific to the SSB network in Switzerland and based on yearly transformation between 1971 and 2000 (Spielmann *et al.*, 2007).

Land transformation in the SGR-model is calculated based on the area transformed to build the railway line. Only Right-of-Way areas have been considered resulting in a total of 3687.47 Ha of land transformation (about 68.2 m^2/m railway line) (ERM, 2019, pp. 290–292). Facilities areas are excluded since they include borrow pits and quarry sites, and this could lead to double counting of land transformation impacts (for example land transformations are already included in gravel production). Moreover, they also include campsites which are temporary transformation of land.

Land occupation impact is also calculated based on the Right-of-Way areas. Since land occupation impact has a unit in m2a (m^2*year), the total area in m^2 is multiplied by the assumed calculation period of 60 years resulting in 4092 m2a/m railway line.

Land transformation impact is included in the construction stage of the infrastructure while land occupation is included in the maintenance stage described in the following section.

4.4 Infrastructure maintenance

4.4.1 Categories of maintenance

Maintenance activities related to the SGR are grouped into three categories in the ESIA report (ERM, 2019, pp. 71–72): "regular maintenance", "investment maintenance", and "unplanned maintenance".

"Regular maintenance" consists of planned maintenance activities which have the purpose to prevent failure of track components while "investment maintenance" consists of repairs or reconstructions not handled by regular maintenance. "Unplanned maintenance" is carried out in case of destruction of railway components after accidents or geological/meteorological events such as landslides or floods. (ERM, 2019, pp. 71–72)

4.4.2 Maintenance activities in the SGR-model

Due to a lack of quantitative information about the maintenance activities, the SGR-model includes only a few regular maintenance activities involving the disposal of track components and the use of new components are considered:

- Rail, sleepers, and fasteners renewal.
- Ballast cleaning, tamping and renewal.

In addition, only maintenance regarding the tracks is included in the model. Maintenance of any other component of the infrastructure is excluded.

It is challenging to assess the frequency of maintenance activities because it depends on local parameters as well as unpredictable events which could affect the service life of the components. The method adopted in this study to determine the frequency of maintenance activities in the SGR-model is described the following paragraphs.

According to a personal communication (AH Løhren 2020, personal communication, 8 May), frequency of maintenance activities can usually be estimated by dividing the theoretical service life of rail components in million gross tonnes (MGT) by the traffic tonnage, also in MGT. Ranges of values for components service life are shown in Table 4.13 (Lichtberger, 2007).

Table 4.13 – Railway components service life

Maintenance activity	Component service life (MGT - million gross tonnes)	
	min	max
Rail renewal	300	1000
Sleeper renewal	350	700
Fastenings renewal	100	500
Ballast tamping	40	70
Ballast cleaning	150	300
Ballast renewal	200	500
Source: (Lichtberger, 2007)		

Lifetime of rail components may vary greatly depending on local parameters such as the track geometry, the ballast quality, the rolling stock, or the climate resulting in broad ranges of service life values but the SGR is a newly built railway line and the track is certainly of good quality, therefore values in the upper part of the ranges can be used to estimate the maintenance frequency (AH Løhren 2020, personal communication, 8 May).

However, the theoretical service life values of rail components have probably been estimated for European conditions and a high annual traffic tonnage is expected. To take these specifications into consideration, the tonnage value calculated in section 4.1.3 (24.56 MGT/year) can be multiplied by 1.1 to estimate maintenance frequency for the SGR (AH Løhren 2020, personal communication, 8 May). Thus, the traffic tonnage considered is 27.02 MGT/year. The frequency of maintenance activities is presented in Table 4.14.

Table 4.14 – Description of maintenance activities in the SGR-model

Maintenance activity	Frequency (times)[a]	Comment	Machinery[b]
Rail renewal	2	Entire component (+pads renewal)	Rail laying machine
Sleeper renewal	2	Entire component	Sleeper laying machine
Fastenings renewal	2	Entire component	-
Ballast tamping	15	Addition of 5% of ballast quantity	Ballast tamping machine
Ballast cleaning	3	Addition of 30% of ballast quantity	Ballast cleaning machine, ballast tamping
Ballast renewal	2	Entire component	Ballast changing machine, ballast tamping machine
Sources: [a]based on calculations with values from (Lichtberger, 2007), [b](Kiani, Parry and Ceney, 2008)			

A few adjustments have been made between the life expectancy calculated (component service life/traffic tonnage).

- The estimated life expectancy of rails is estimated to be the same as the sleepers (700 MGT) to have rail renewal and sleeper renewal occurring at the same time: every 25 years. In addition, a life expectancy of 1000 MGT for rails is for tangent tracks and decreasing the life expectancy to 700 MGT results in considering some curved tracks which have a lower life expectancy (Cannon *et al.*, 2003).
- The life expectancy of fastenings and ballast (500/27.02 =18.5 years) have been rounded to 20 years.
- Rounding to the closest integer have also been performed for ballast tamping and ballast cleaning activities resulting in a ballast tamping every 3 years between two ballast renewal and one ballast cleaning 12 years after one ballast renewal.

As mentioned by Kiani, Parry and Ceney (2008), supplementation of ballast occurs during cleaning and tamping activities. A tamping machine is used to adjust the track geometry after ballast cleaning and after ballast renewal during maintenance works (AH Løhren 2020, personal communication, 15 May). As for the construction of new track, it is then chosen to add the use of tamping machine after ballast cleaning and ballast renewal even if it is not specified in Kiani, Parry and Ceney (2008).

The maintenance activities which are included in the SGR-model are also represented chronologically in Figure 4.3.

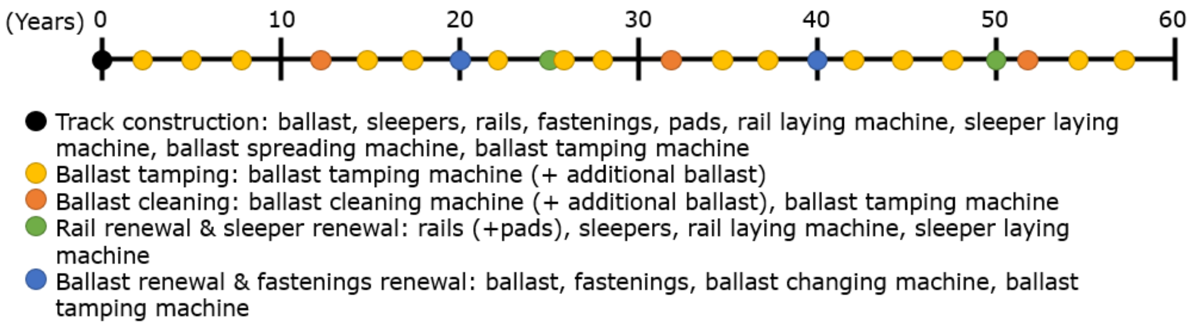

Figure 4.3 – Maintenance activities and machinery in the SGR-model

Some maintenance activities occur before the end of the calculation period, but life service of the changed components is longer than the time left (for example, rails are changed at year 50 but have a life service of 25 years). In the SGR-model, only the share of the used service life during the calculation period is included (for the rails changed at year 50, only 10/25=0.4 i.e. 40% of the rails is included in the SGR-model). Table 4.15 presents the number of maintenance activities included in the environmental impact assessment of the SGR-model maintenance phase.

Table 4.15 – Maintenance activities included in the environmental impact assessment of the SGR-model maintenance phase

Rail renewal	Sleepers renewal	Fastenings renewal	Pads renewal	Ballast tamping	Ballast cleaning	Ballast renewal
1.4	1.4	2	1.4	15	3	2

4.5 Infrastructure end-of-life

End-of-life management of the whole infrastructure can be distinguished from the end-of-life of the components during maintenance (Asplan Viak AS, 2011). Infrastructure disposal is excluded from the SGR-model because of the high uncertainty regarding the fate of the infrastructure. However, disposal of track components is considered when these components are replaced by new ones.

Based on the cut-off approach, three options for disposal of materials exist: direct recycling, direct disposal, and partial recycling and disposal after sorting in a waste treatment facility (Doka, 2009). For the disposal railway component, the following end-of-life management is considered:

- Pads: direct disposal including transport (200 km) by truck and landfilling.
- Fastenings: direct recycling (impacts from transport and recycling processes allocated to the secondary steel produced from these fastenings).
- Rails: direct recycling (only impacts from dismantling allocated to the rails, impacts from transport and recycling processes allocated to the secondary steel produced from these rails).
- Sleepers: direct recycling (only impacts from dismantling allocated to the sleepers, impacts from transport and recycling processes allocated to the secondary steel and aggregates produced from crushing the sleepers).
- Ballast: direct recycling (impacts from transport and recycling processed allocated to the secondary aggregates produced from ballast).

When maintenance activities are occurring, it is obvious that the disposal of the components occurs shortly after the maintenance. However, for the components whose life service is longer than the time left (for example, rails are changed at year 50 but have a life service of 25 years). Some part of the disposal activities is allocated to these components, this part corresponds to the share of the used service life during the calculation period (for the rails changed at year 50, only 10/25=0.4 i.e. 40% of their future disposal is included in the SGR-model).

4.6 Overview

In this life cycle inventory, assumptions have been made to build the SGR-model and overcome the lack of project-specific data. Main assumptions are listed below:

- Rolling stock has been estimated based on the total kilometres needed over 60 years by using kilometric lifetime performance of rail vehicles from Ecoinvent database v3.2 (Wernet *et al.*, 2016).
- Operation in the SGR-model only consists of operations of rail vehicles transporting passengers and freight. No operation of infrastructure has been included.
- Vegetation clearance is source of CO_2 emissions. Only these emissions from vegetation removal are considered in the SGR-model. Even if diesel machineries are used for this activity, their use has not been estimated.
- Earthworks are assumed to only correspond to cut and fill activities for open sections. Specific excavated material volume for tunnels and crossing structures have been included in the SGR-model.
- All tunnels, crossing structures and culverts are assumed to require the same material and energy quantities than their respective modelled process in the SGR-model. However, one may see that this only corresponds to an assumption by watching online videos available on the YouTube channel of Yapı Merkezi Tanzania (Yapı Merkezi Tanzania, no date) in which every piece of crossing structure or culvert seems to have its own construction dimensions.
- Track components and power and signalling system are assumed to be the same all along the track (main line, in tunnel, on crossing structures & viaduct, and sidings).
- Only two types of steel used in this inventory: reinforcing steel and low-alloyed steel (steel used for rails is also assumed to be low-alloyed steel).
- Maintenance processes only regard planned maintenance of track components.

In appendix (Appendix B7), complete tables providing material and energy requirements for construction, maintenance, and end-of-life stages are available.

5 Life Cycle Impact Assessment

In this chapter, life cycle impact assessment results are presented. Since both passengers and freight trains will use the SGR, allocation factors are calculated in the second section to further allocate the environmental impacts from the infrastructure.

5.1 Environmental impact assessment

Environmental impacts are presented in the following way. First, impacts resulting from the whole SGR-model are detailed. Then impacts from each subsystem (operation, infrastructure, and rolling stock) are investigated.

5.1.1 Contribution analysis: the SGR-model

The environmental impacts of the SGR-model over the 60-year calculation period are shown in Figure 5.1. The figure illustrates how each subsystem (infrastructure, rolling stock, operation) contributes to the various impact categories. Table 5.1 presents the results by impact category for each subsystem as well as the total impact values.

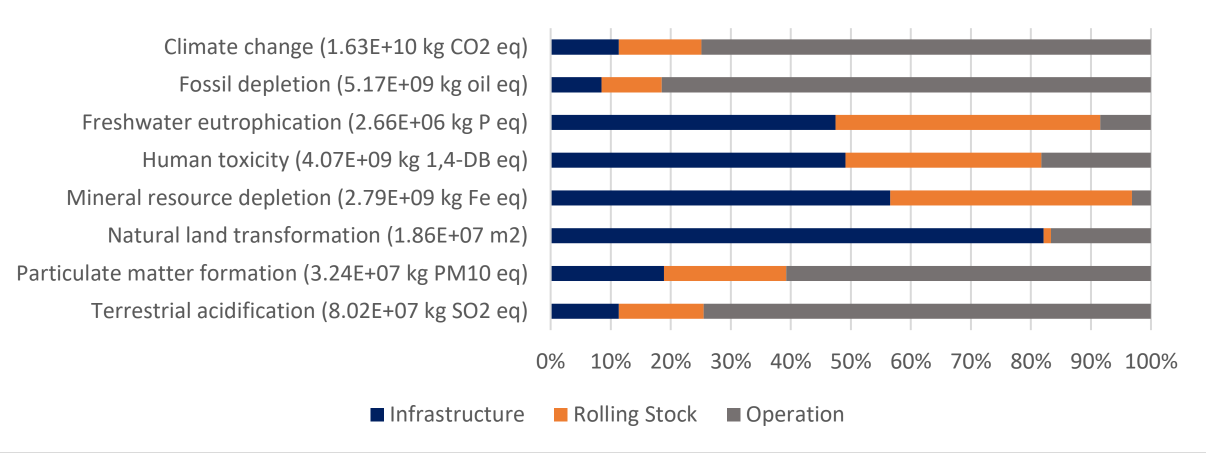

Figure 5.1 - Environmental impacts of SGR-model broken down into infrastructure, rolling stock, and operation

Operation phase represents 75% of impact in climate change of the SGR-model. Moreover, operation phase is also responsible for 82% of fossil depletion,74% of terrestrial acidification, and 61% of particulate matter formation. The lowest contributions from the operation phase is found in mineral resource depletion where it causes only 3% of the impact. For this impact category as well as for freshwater eutrophication, human toxicity and natural land transformation, infrastructure has the largest contribution.

Table 5.1 - Environmental impacts of SGR-model broken down into infrastructure, rolling stock, and operation

Impact category	Infrastructure	Rolling Stock	Operation	Total
Climate change	1.85E+09	2.24E+09	1.22E+10	1.63E+10
Fossil depletion	4.38E+08	5.17E+08	4.21E+09	5.17E+09
Freshwater eutrophication	1.26E+06	1.18E+06	2.25E+05	2.66E+06
Human toxicity	2.00E+09	1.33E+09	7.44E+08	4.07E+09
Mineral resource depletion	1.58E+09	1.12E+09	8.83E+07	2.79E+09
Natural land transformation	1.53E+07	2.26E+05	3.10E+06	1.86E+07
Particulate matter formation	6.11E+06	6.62E+06	1.97E+07	3.24E+07
Terrestrial acidification	9.12E+06	1.13E+07	5.97E+07	8.02E+07

5.1.2 Operation

Operation phase is the most contributing subsystem to the SGR-model. Environmental impacts come from indirect emissions in electricity production and direct emissions included in the SGR-model (SF_6 emitted at substations, particulates emitted to air and iron emitted to soil). Table 5.2 provides environmental impacts from direct and indirect emissions from operation phase for both passenger and freight transport.

Table 5.2 - Environmental impacts of the SGR-model operation phase - Indirect em. = indirect emissions from electricity production to power rail vehicles / Direct em. = direct emissions from vehicles operation.

Impact category	Passenger transport operation			Freight transport operation			Total operation
	Indirect em.	Direct em.	Total	Indirect em.	Direct em.	Total	
CC (kg CO2 eq)	6.33E+08	9.65E+05	6.34E+08	1.15E+10	1.76E+07	1.15E+10	1.22E+10
FD (kg oil eq)	2.19E+08	0.00E+00	2.19E+08	3.99E+09	0.00E+00	3.99E+09	4.21E+09
FE (kg P eq)	1.17E+04	0.00E+00	1.17E+04	2.13E+05	0.00E+00	2.13E+05	2.25E+05
HT (kg 1,4-DB eq)	3.87E+07	0.00E+00	3.87E+07	7.05E+08	0.00E+00	7.05E+08	7.44E+08
MRD (kg Fe eq)	4.60E+06	0.00E+00	4.60E+06	8.37E+07	0.00E+00	8.37E+07	8.83E+07
NLT (m2)	1.61E+05	0.00E+00	1.61E+05	2.94E+06	0.00E+00	2.94E+06	3.10E+06
PMF (kg PM10 eq)	8.56E+05	3.77E+05	1.23E+06	1.56E+07	2.85E+06	1.85E+07	1.97E+07
TA (kg SO2 eq)	3.11E+06	0.00E+00	3.11E+06	5.66E+07	0.00E+00	5.66E+07	5.97E+07

Regarding direct emissions from operations, SF_6, a powerful GHG with a GWP value for 100-year time horizon of 22800[10] only contributes to climate change impact. This gas is responsible for only 0.15% of the impact. Particulates and more specifically particulates with a size comprised between 2.5 and 10 µm contribute only to particulate matter formation with a contribution value of 16.4%. Based on the Excel spreadsheet containing the characterisation factors from ReCiPe impact assessment method version 1.11 (Goedkoop *et al.*, 2013, 2014), no characterisation factor was found for particulates with a size greater than 10 µm as well as iron emitted to soil. Therefore, this explains why Arda does not return contribution results from these environmental stressors to any impact categories.

[10] GWP value used in ReCiPe v1.11 comes from the IPCC fourth assessment report published in 2007 (Forster *et al.*, 2007; Goedkoop *et al.*, 2013)

The rest of the environmental impacts from operation phase stems from indirect emissions related to electricity production. Regarding climate change impact, when investigating the global warming potential of 1 kWh of high-voltage electricity in Tanzania, the highest contributions are from electricity production from natural gas (45% of GWP of 1 kWh electricity) and from oil (40.5% of GWP of 1 kWh electricity).

5.1.3 Infrastructure

Even if the infrastructure does not stand out as the main responsible of environmental impacts from the SGR-model, it has a high contribution in some impact categories especially to natural land transformation (82%), but also mineral resource depletion (57% contribution), freshwater eutrophication (47% contribution) and human toxicity (49% contribution). When it comes to evaluate where the impacts from the operation phase comes from, it is rather easy to identify that electricity is the key element to focus on to mitigate environmental impacts. However, many processes are included in the infrastructure subsystem and identifying key elements to address to improve its environmental performance require further investigations.

5.1.3.1 Environmental impacts of the whole infrastructure life cycle

Figure 5.2 presents the contribution of each life cycle stage to the global impacts of the infrastructure. Environmental impact results are provided in Table 5.3.

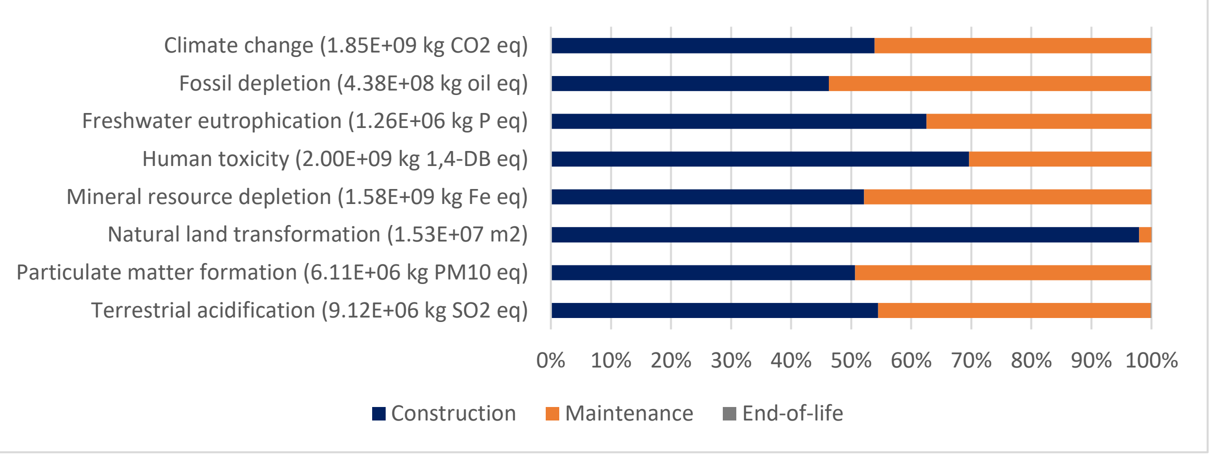

Figure 5.2 - Environmental impacts of the SGR-model infrastructure by life cycle stage

The contribution of end-of-life stage is nearly invisible (contribution lower than 0.2% for all impact categories). Construction and maintenance phases have a rather balanced contribution to the infrastructure environmental impacts over the 60-year life cycle except to natural land transformation for which the construction stage covers about 98% of the impact.

Table 5.3 - Environmental impacts of the SGR-model infrastructure by life cycle stage

Impact category	Infrastructure			Total infrastructure
	Construction	Maintenance	End-of-life	
Climate change (kg CO2 eq)	9.95E+08	8.48E+08	1.74E+06	1.85E+09
Fossil depletion (kg oil eq)	2.03E+08	2.35E+08	5.50E+05	4.38E+08
Freshwater eutrophication (kg P eq)	7.90E+05	4.73E+05	7.87E+01	1.26E+06
Human toxicity (kg 1,4-DB eq)	1.39E+09	6.06E+08	8.59E+05	2.00E+09
Mineral resource depletion (kg Fe eq)	8.23E+08	7.56E+08	6.03E+04	1.58E+09
Natural land transformation (m2)	1.49E+07	3.16E+05	4.21E+02	1.53E+07
Particulate matter formation (kg PM10 eq)	3.10E+06	3.01E+06	6.33E+03	6.11E+06
Terrestrial acidification (kg SO2 eq)	4.97E+06	4.14E+06	1.23E+04	9.12E+06

Environmental impacts can also be broken down into contribution of materials, land use change, transport, and energy as shown in Figure 5.3. Table 5.4 provides the environmental impact results.

Materials in the life cycle inventory are grouped into the following categories: steel (low-alloyed), reinforcing steel, concrete, cement, gravel, explosives, plastics[11] (rubber for pads and PVC for membrane in tunnel), copper, bronze, aluminium, and processing metals. Processing metals correspond to the metalworking processes such as hot rolling of steel. All these categories are comprised in the group of materials. Land use change comprises vegetation clearance, and land transformation occurring at the construction stage. Energy corresponds to electricity, diesel & machinery as well as excavation work. Transport is both shipping transport for import of materials and road transport by lorry.

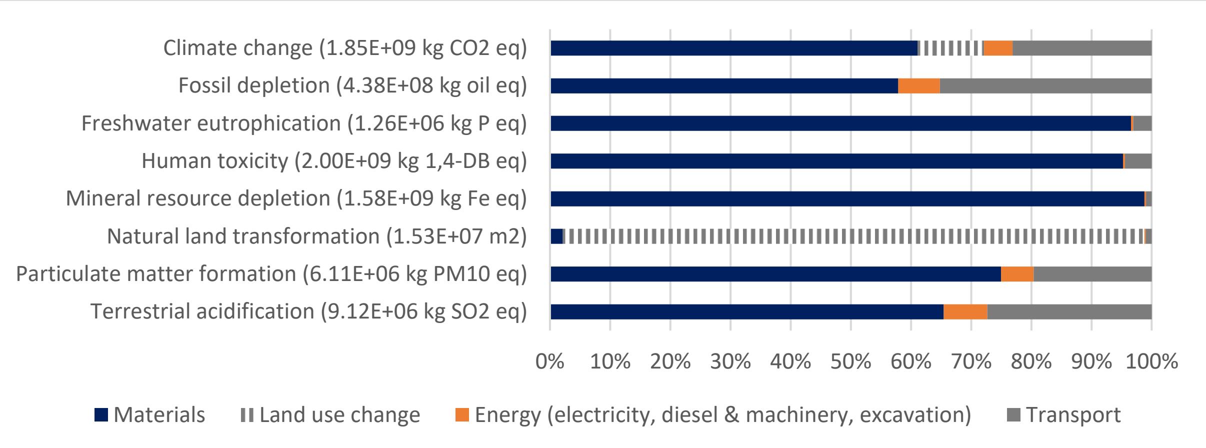

Figure 5.3 - Environmental impacts of the SGR-model infrastructure broken down into materials, land use and land use change, energy, and transport

Except for natural land transformation, materials are the main responsible of environmental impacts. Their contribution is up to nearly 99% to mineral depletion, 97% to freshwater eutrophication, and 95% to human toxicity. Transport is the second contributor amounting for up to 35% of fossil depletion. Energy has a rather low contribution: its highest contributions are about 7% to terrestrial acidification and fossil depletion. Land use change present environmental impacts only in climate change and

[11]To note: impacts from landfilling of rubber pads are included in the impacts from plastics.

natural land transformation due to CO_2 emissions from vegetation clearance and land transformation at the construction stage. Yet, these contributions are far from being negligible: contribution to climate change averages 11% of the impact and contribution to natural land transformation reaches 97%.

Table 5.4 - Environmental impacts of the SGR-model infrastructure broken down into materials, land use change, energy, and transport

Impact category	Materials	Land use change	Energy	Transport	Total inf.
Climate change (kg CO2 eq)	1.13E+09	2.03E+08	8.77E+07	4.27E+08	1.85E+09
Fossil depletion (kg oil eq)	2.54E+08	0.00E+00	3.04E+07	1.54E+08	4.38E+08
Freshwater eutrophication (kg P eq)	1.22E+06	0.00E+00	4.79E+03	3.89E+04	1.26E+06
Human toxicity (kg 1,4-DB eq)	1.90E+09	0.00E+00	6.00E+06	8.93E+07	2.00E+09
Mineral resource depletion (kg Fe eq)	1.56E+09	0.00E+00	4.30E+06	1.47E+07	1.58E+09
Natural land transformation (m2)	3.24E+05	1.47E+07	2.84E+04	1.51E+05	1.53E+07
Particulate matter formation (kg PM10 eq)	4.58E+06	0.00E+00	3.29E+05	1.20E+06	6.11E+06
Terrestrial acidification (kg SO2 eq)	5.97E+06	0.00E+00	6.61E+05	2.49E+06	9.12E+06

A table presenting the disaggregation of environmental impacts from materials, energy, and transport is available in appendix (Appendix C1).

It is interesting to determine which processes among materials, land use change, energy and transport are the main contributors to the various impact categories. Table 5.5 presents the four processes contributing the most to the environmental impacts of the SGR-model.

Table 5.5 – Main processes contributing to the environmental impacts of the SGR-model infrastructure

Impact category	1st contributor		2nd contributor		3rd contributor		4th contributor		Total
CC (kg CO2 eq)	Steel (low-alloyed)	34%	Transport - Lorry	21%	Land use change	11%	Concrete	9%	75%
FD (kg oil eq)	Steel (low-alloyed)	34%	Transport - Lorry	32%	Gravel	8%	Processing metals	5%	80%
FE (kg P eq)	Steel (low-alloyed)	54%	Copper	23%	Bronze	6%	Gravel	5%	88%
HT (kg 1,4-DB eq)	Steel (low-alloyed)	45%	Copper	34%	Bronze	8%	Transport - Lorry	4%	91%
MRD (kg Fe eq)	Steel (low-alloyed)	85%	Copper	6%	Reinforcing steel	3%	Bronze	2%	96%
NLT (m2)	Land use change	97%	Gravel	1%	Transport - Lorry	1%	Steel (low-alloyed)	0.4%	99%
PMF (kg PM10 eq)	Steel (low-alloyed)	49%	Transport - Lorry	15%	Gravel	8%	Copper	5%	77%
TA (kg SO2 eq)	Steel (low-alloyed)	31%	Transport - Lorry	19%	Copper	10%	Gravel	9%	68%

As it can be seen from the table above, steel (low-alloyed) is the first contributor to all impact categories except natural land transformation for which land transformation takes the first place. Across the impact categories, the second most important contributors are transport by lorry, copper, and gravel. Copper specifically has a large contribution in two impact categories: freshwater eutrophication and human toxicity. Moreover, grouped with steel (low-alloyed), the two metals contribute to nearly 80% of these two impacts.

Environmental impacts resulting from the infrastructure can also be broken down into the different components (vegetation clearance & land transformation, earthworks, track, power and signalling system, tunnel, crossing structures and culverts) as shown in Figure 5.4. Environmental impact results are provided in Table 5.6.

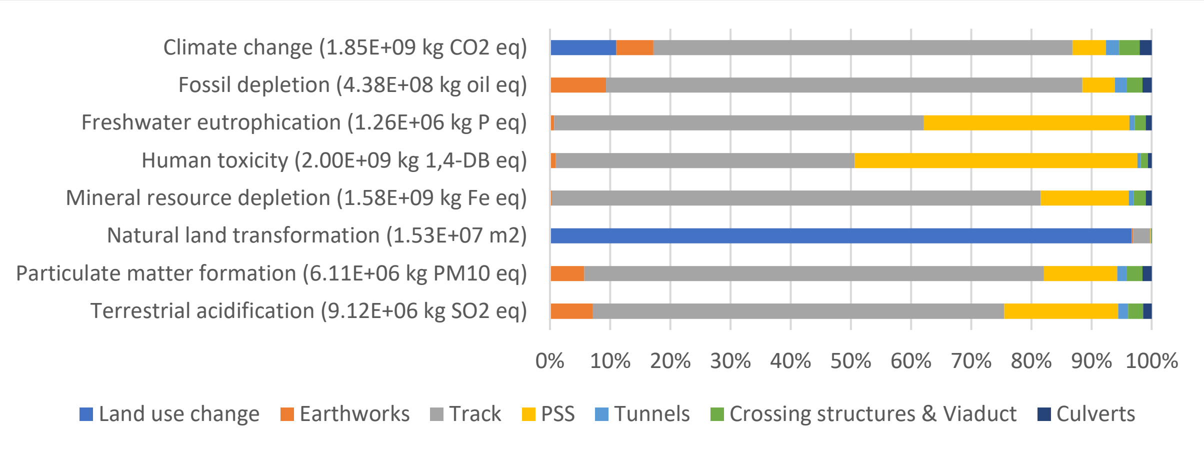

Figure 5.4 - Environmental impacts of the SGR-model infrastructure broken down into land use change, earthworks, track, power and signalling system, tunnels, crossing structures & viaduct, and culverts

When looking at environmental impact results and excluding natural land transformation, track account for a large share of all the environmental impacts (highest contribution, 81%, to mineral resource depletion and lowest contribution, 50%, to human toxicity). Power and signalling system is the second largest contributor with its highest impact to human toxicity (47% contribution). Earthworks contribution is also noticeable with a contribution up to 9% to fossil depletion. A rather limited contribution from tunnels, crossing sections and culverts is observed: these three components together present their highest contribution to 7.6% to climate change.

Table 5.6 - Environmental impacts of the SGR-model infrastructure broken down into land use change, earthworks, track, power and signalling system, tunnels, crossing structures, and culverts - Earth. = Earthworks, PSS = Power and signalling system, Crossing str. = Crossing structures, Total inf. = Total infrastructure

Impact category	Land use change	Earth.	Track	PSS	Tunnels	Crossing str.	Culverts	Total inf.
CC (kg CO2 eq)	2.03E+08	1.14E+08	1.28E+09	1.04E+08	4.02E+07	6.25E+07	3.68E+07	1.85E+09
FD (kg oil eq)	0.00E+00	4.08E+07	3.47E+08	2.38E+07	8.48E+06	1.15E+07	6.75E+06	4.38E+08
FE (kg P eq)	0.00E+00	9.15E+03	7.76E+05	4.32E+05	1.12E+04	2.30E+04	1.22E+04	1.26E+06
HT (kg 1,4-DB eq)	0.00E+00	1.90E+07	9.94E+08	9.39E+08	1.14E+07	2.43E+07	1.20E+07	2.00E+09
MRD (kg Fe eq)	0.00E+00	5.44E+06	1.28E+09	2.31E+08	1.35E+07	3.15E+07	1.52E+07	1.58E+09
NLT (m2)	1.47E+07	3.96E+04	4.28E+05	1.73E+04	6.10E+03	8.30E+03	4.90E+03	1.53E+07
PMF (kg PM10 eq)	0.00E+00	3.49E+05	4.67E+06	7.45E+05	9.44E+04	1.62E+05	9.23E+04	6.11E+06
TA (kg SO2 eq)	0.00E+00	6.49E+05	6.24E+06	1.73E+06	1.53E+05	2.24E+05	1.30E+05	9.12E+06

5.1.3.2 Environmental impacts of railway components

To have a better understanding of environmental impacts from each railway component, a contribution analysis for each component is required. In this section, contribution analyses are only presented in figures, but tables of environmental impacts are provided in appendix (Appendix C2). First, environmental impacts from earthworks at the construction stage are presented in Figure 5.5.

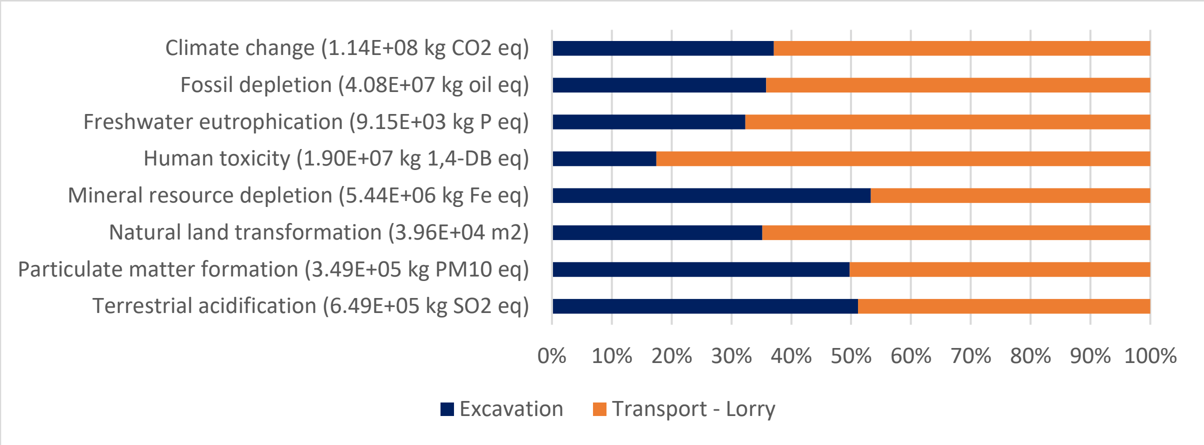

Figure 5.5 – Environmental impacts from earthworks

Despite transporting only half of volume estimated for excavation activities, impacts from transport by lorry range from 47% (mineral resource depletion) to 83% (human toxicity).

Environmental impacts from processes included in the life cycle of tracks are shown in Figure 5.6. Construction, maintenance, and disposal stages are included in the results presented in this figure.

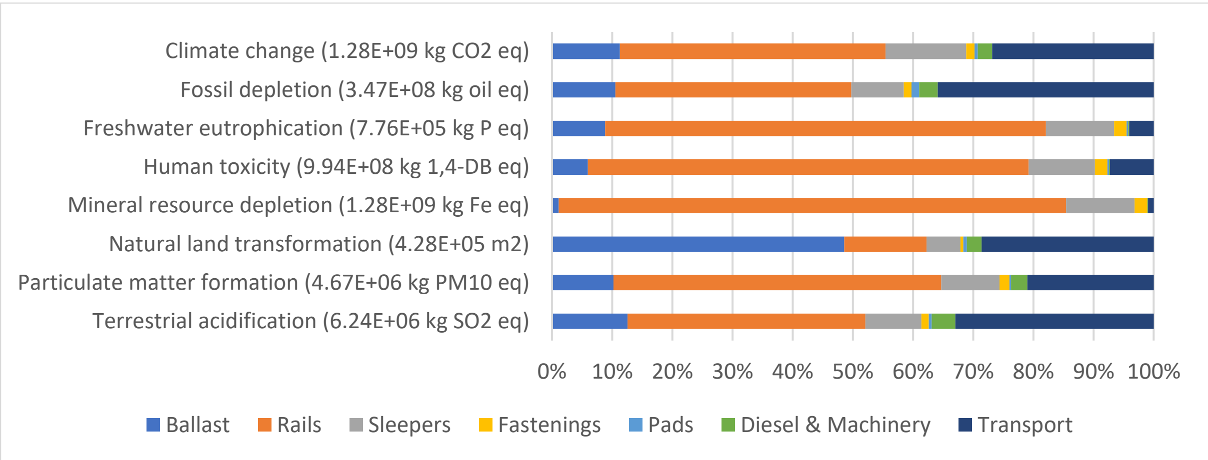

Figure 5.6 - Environmental impacts from track

Rails and transport are the two main contributors. More specifically, these impacts stem from the production of steel (low-alloyed) for rails and transport of ballast. On one hand, steel covers more than 90% of rail environmental impacts (except for natural land transformation for which steel covers 87% of the impact). On the other hand, transport of ballast covers more than 80% of impacts from transport (except for terrestrial acidification for which transport of ballast covers 63% of the impact). The high contribution from ballast to natural land transformation comes from gravel production which is the only input included in this subcomponent.

It was shown in Figure 5.4 that, in several impact categories, power and signalling system has the second largest contribution. A contribution analysis of this railway component is depicted in Figure 5.7.

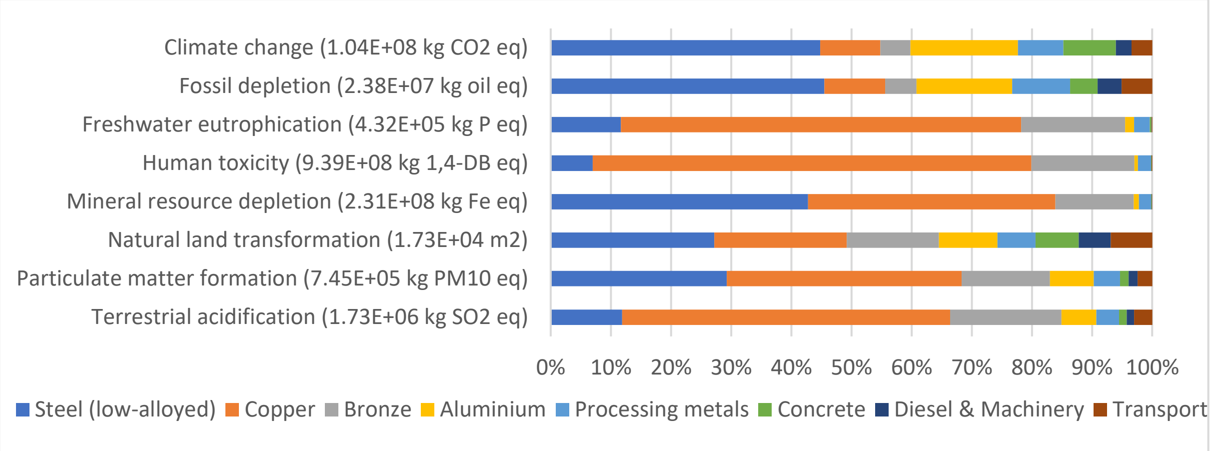

Figure 5.7 - Environmental impacts from power and signalling system

In comparison with track, transport has rather low contribution to impacts from power and signalling system. Steel (low-alloyed) and copper productions have the greatest contributions. Copper is especially a high contributor to freshwater eutrophication and human toxicity by contributing respectively to 67% and 73% of the impacts. Steel presents its highest contributions to climate change (45% contribution) and fossil depletion (46% contribution). Both metals have a similar contribution to mineral resource depletion.

Environmental impacts from inputs of materials and energy to tunnel construction are presented in Figure 5.8.

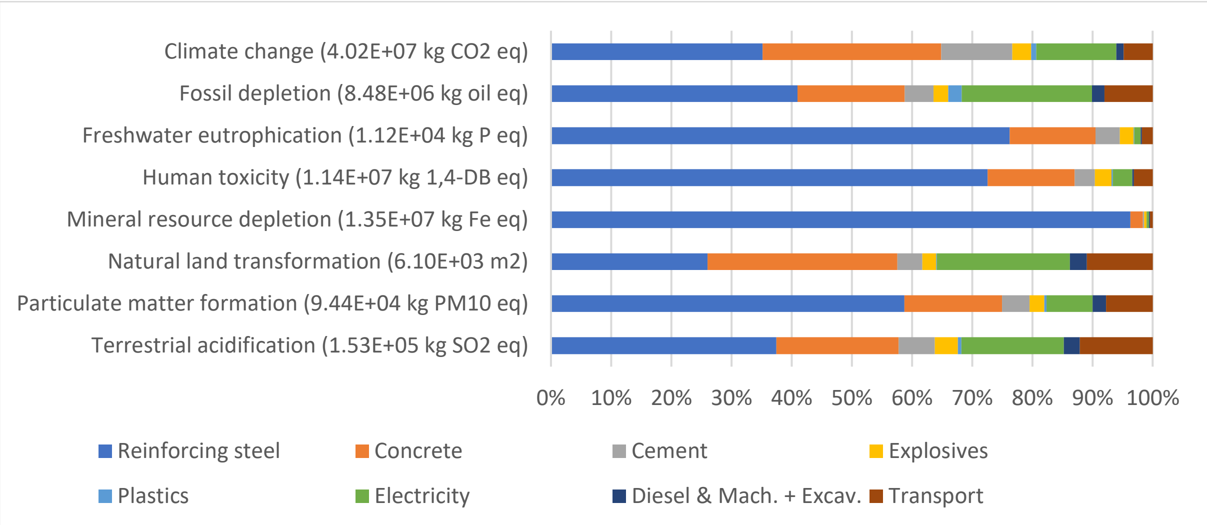

Figure 5.8 - Environmental impacts from tunnels

Reinforcing steel is the most contributing input, its contribution ranges between 26% to natural land transformation and 96% to mineral resource depletion. Concrete, electricity, and transport are the next most contributing inputs. Cement does not have a significant contribution except to climate change, where it represents 12% of the impact. Furthermore, as it can be noticed for track and power and signalling system, the use of machinery has a low contribution to environmental impacts.

Figure 5.9 and Figure 5.10 present environmental impacts from crossing structures & viaduct, and culverts.

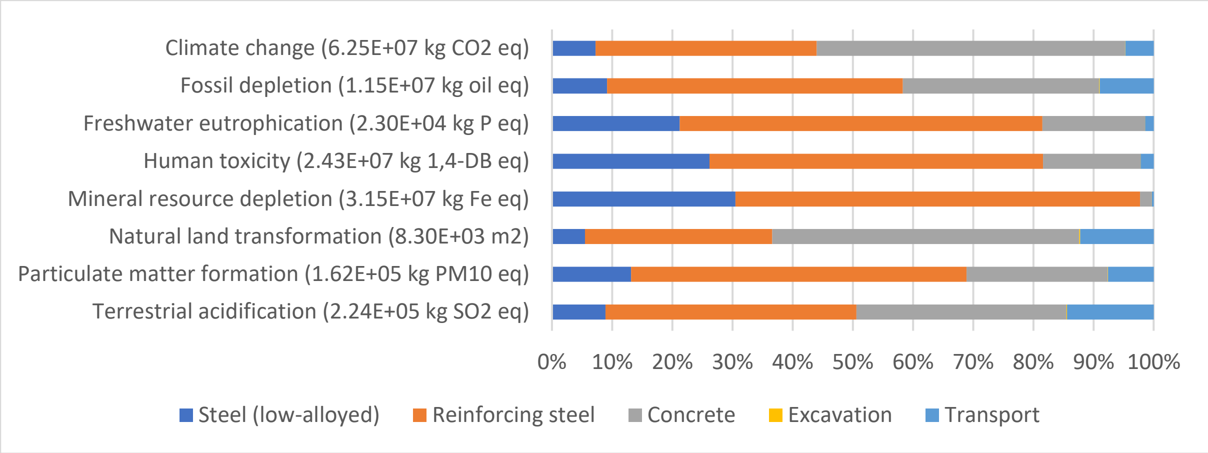

Figure 5.9 - Environmental impacts from crossing structures & viaduct

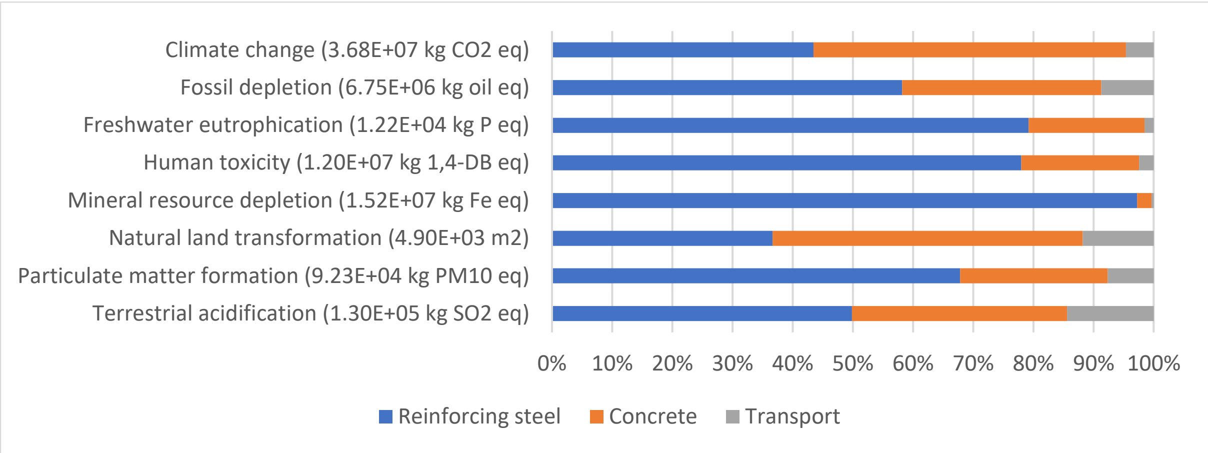

Figure 5.10 – Environmental impacts from culverts

The two contribution analyses are similar when steel (low-alloyed) and reinforcing steel are grouped and compared with concrete and transport contributions. This result is expected since the amount of steel for culverts was estimated based on the ratio steel volume/concrete volume required in the construction of crossing structures (which is also similar to the ratio for viaduct). Globally, steel low-alloyed and reinforcing steel dominate the impacts. In a few categories, concrete has the highest contribution such as in climate change or natural land transformation where its contribution is slightly above 50%.

5.1.3.3 Environmental impacts by section

Railway components can be grouped to divide the railway line into three types of section: tunnel sections, crossing structure sections and open sections. Tunnel sections correspond to track sections in tunnels. Crossing structure sections correspond to track sections on viaduct, bridges, above underpasses, or animal/pedestrian passages. It is assumed that tunnels and crossing structure sections are single-track sections. Lastly, open sections correspond to the rest of the track including sidings. The sum of the sections' lengths is equal to the track route length (541 km).

Table 5.7 – Length (m) and share (%) of each section (open section, tunnel section, crossing structure section) in the SGR-model

Section type	Length (m)	%
Open section	529,800	97.9%
Tunnel section	2620	0.5%
Crossing structure (& viaduct) section (excluding overpasses)	8580	1.6%

The different components (vegetation clearance & land transformation, earthworks, track, power and signalling system, tunnel, crossing structures and culverts) are allocated to each section type based on allocation factors calculated and presented in Table 5.8.

Table 5.8 – Allocation of each component to the different types of section (open section, tunnel section, crossing structure section)

Section type	% allocation							
	Land use change	Earthwork	Track	PSS	Tunnels	Crossing structures	Viaduct	Culverts
Open section	97.9%	100%	98.4%	98.4%	0%	24.2%	0%	100%
Tunnel section	0.5%	0%	0.4%	0.4%	100%	0.0%	0%	0%
Crossing structure section	1.6%	0%	1.2%	1.2%	0%	75.8%	100%	0%

Vegetation clearance & land transformation (over 541 km) are allocated to each section type according to the respective section share. Earthworks (cut and fill activities) are allocated to the open section since specific earthworks have been assumed for tunnels and crossing structures. Track (total length of 722 km including sidings) are allocated based on tunnels and crossing structures length and the rest is allocated to open section. The same approach is used for power and signalling system. Tunnels are allocated to tunnel section. Crossing structures are allocated to both crossing structure section and open section while viaduct is only allocated to crossing structure section. Indeed, overpasses are allocated to open sections since they cross the tracks and are meant to be used by road users. Culverts are all allocated to open section.

From this allocation, environmental impacts for each section are calculated and divided by the respective section length to obtain the environmental impacts per section metre. A table presenting these results is available in appendix (Appendix C3). Regarding total environmental impacts per section, open section covers more than 95% of the impacts for all impact categories. This result is not surprising since 97.9% of the track is open section. A comparison of environmental impact per section metre is therefore necessary to highlight differences in environmental impacts between the three section types.

Figure 5.11 illustrates the comparison between impacts from open section and crossing structure section with the impacts from tunnel section.

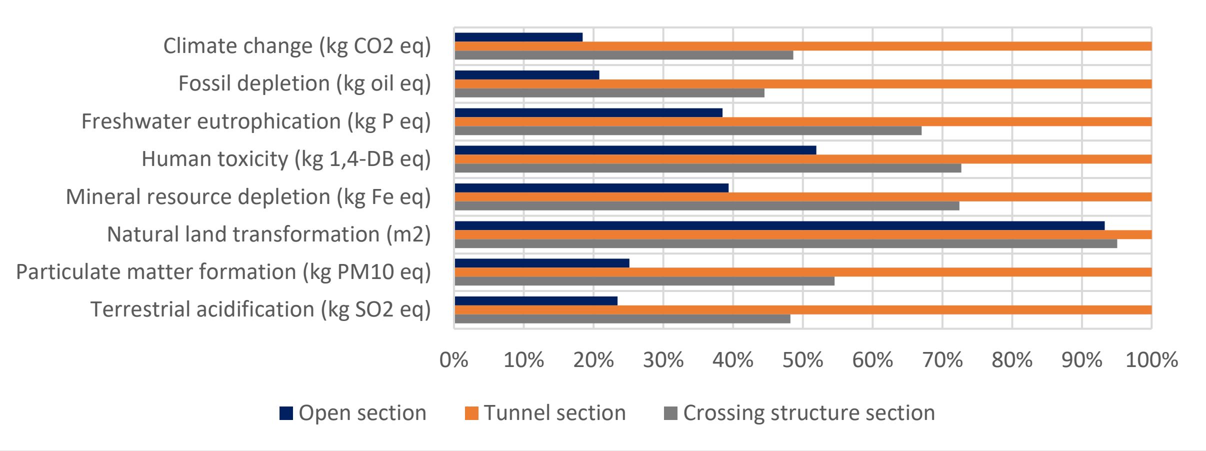

Figure 5.11 – Comparison of environmental impacts for 1 metre section type in the SGR-model (open section, tunnel section and crossing structure section)

Tunnel section presents the highest impact values per metre in all impact categories followed by crossing structure section. Even if both tunnel and crossing structure sections are single-track sections while open sections also includes sidings, their impacts per metre are higher. This can be explained by the large use of steel and concrete as input materials.

5.1.4 Rolling stock

One surprising outcome of the environmental impact results of the SGR-model is the large contribution of the rolling stock in several impact categories as depicted in Figure 5.1.

Figure 5.12 presents the environmental impacts from the rolling stock broken down into passenger trains, freight locomotives and goods wagons (the figure is in logarithmic scale to show the impacts from passenger trains and locomotives).

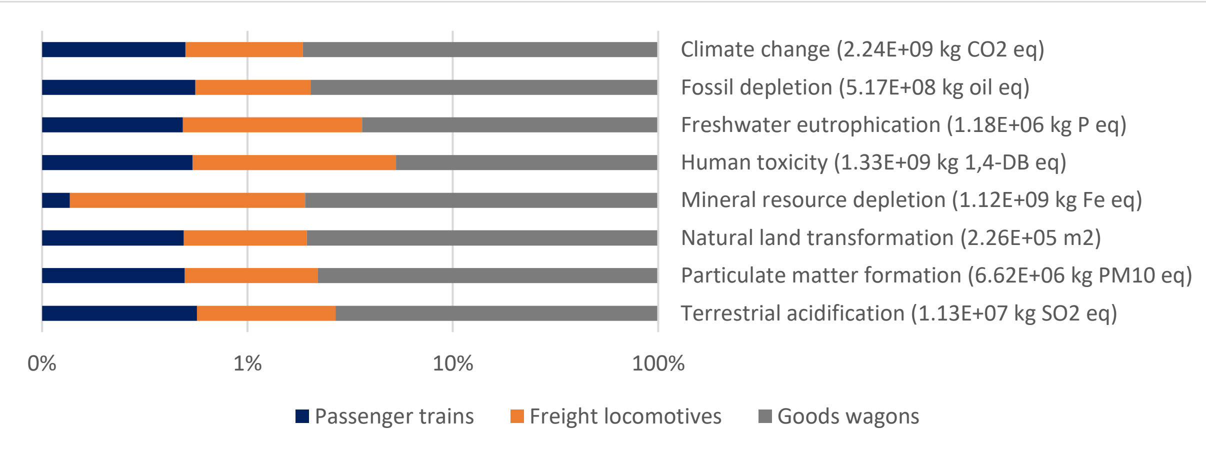

Figure 5.12 – Environmental impacts from rolling stock broken down into passenger trains, freight locomotives, and goods wagons (the figure is in logarithmic scale)

An analysis of the rolling stock reveals that goods wagons cover more than 95% of the environmental impact in all categories.

Table 5.9 - Environmental impacts of rolling stock broken down into passenger trains, freight locomotives and goods wagons

Impact category	Passenger trains	Freight trains		
		Freight locomotives	Goods wagons	Total freight
Climate change (kg CO2 eq)	1.12E+07	3.05E+07	2.20E+09	2.23E+09
Fossil depletion (kg oil eq)	2.88E+06	7.59E+06	5.06E+08	5.14E+08
Freshwater eutrophication (kg P eq)	5.70E+03	3.68E+04	1.13E+06	1.17E+06
Human toxicity (kg 1,4-DB eq)	7.15E+06	6.30E+07	1.26E+09	1.32E+09
Mineral resource depletion (kg Fe eq)	1.53E+06	1.99E+07	1.10E+09	1.12E+09
Natural land transformation (m2)	1.11E+03	3.28E+03	2.22E+05	2.25E+05
Particulate matter formation (kg PM10 eq)	3.28E+04	1.13E+05	6.47E+06	6.58E+06
Terrestrial acidification (kg SO2 eq)	6.44E+04	2.39E+05	1.10E+07	1.13E+07

5.2 Allocation between freight and passenger transport

5.2.1 Allocation factors

Allocation of environmental impact is detailed in the Product Category Rules (PCR) 2013:19 for Railways (The International EPD® System, 2019). The SGR is used by freight and passenger trains, this is a "combined use of infrastructure" (The International EPD® System, 2019, p. 10): the allocation is based on the transport work in gross tonne-kilometres (gtkm) and the total distance travelled by the vehicles. Respective share for freight (gtkm(freight)/gtkm(total)) and passengers (gtkm(passengers)/ gtkm(total)) are then multiplied with the total impact from the infrastructure.

In this thesis, gross tonne of vehicles is calculated based on the total weight of vehicles (including weight of locomotives, wagons and goods for freight and including passenger trains and passengers for passengers)[12]. Allocation is summarized by the following formulas:

$$gtkm(freight) = (locomotives\ weight + wagons\ weight + goods\ weight) * total\ km\ freight$$

$$gtkm(passengers) = (passengers\ trains\ weight + passengers\ weight) * total\ km\ passengers$$

$$gtkm(total) = gtkm(freight) + gtkm(passengers)$$

$$\text{Impact infrastructure freight } = \text{total environmental impact infrastructure} * \frac{gtkm(freight)}{gtkm(total)}$$

$$\text{Impact infrastructure passengers } = \text{total environmental impact infrastructure} * \frac{gtkm(passengers)}{gtkm(total)}$$

The allocations factors for passengers and freight are calculated and shown in Table 5.10.

Table 5.10 – Allocation factors for passengers and freight

Allocation of infrastructure impact		
Passengers	gtkm(passenger)/gtkm(total)	0.022
Freight	gtkm(freight)/gtkm(total)	0.978

[12] This definition rather corresponds to the definition of gross-gross tonne kilometre (Spielmann *et al.*, 2007).

These allocation factors mean that 2.2% of the infrastructure is allocated to passenger transport while 97.8% is allocated to freight transport. Most of the environmental impacts from the infrastructure is therefore allocated to freight transport. This is not surprising since the future expected traffic is mainly composed of freight trains as described in section 4.1.1.

Moreover, impact from infrastructure can be calculated per net tonne-kilometres (tkm) for freight and per passenger-kilometres (pkm) for passengers (The International EPD® System, 2019):

$$\text{Impact infrastructure freight (per tkm)} = \frac{\text{Impact infrastructure freight}}{tkm}$$

$$\text{Impact infrastructure passengers (per pkm)} = \frac{\text{Impact infrastructure passengers}}{pkm}$$

The total passenger-kilometre and tonne-kilometre for a 60-year calculation period shown in Table 5.11 are estimations based on future passenger and freight demand described in section 4.1.1.

Table 5.11 – Total passenger-kilometre and tonne-kilometre for a 60-year calculation period

Total pkm	3.57E+10
Total tkm	4.19E+11

5.2.2 Allocation of impacts

Environmental impacts from the SGR-model are allocated to passenger and freight transport. Figure 5.13 is a graph presenting environmental impacts allocation and shows how each subsystem (infrastructure, rolling stock and operation) contribute to passenger transport, freight transport and the whole system. One may see that the contribution of each subsystem to freight transport impacts is nearly the same as for the whole system. This can be explained by freight being the main transport activity of the SGR.

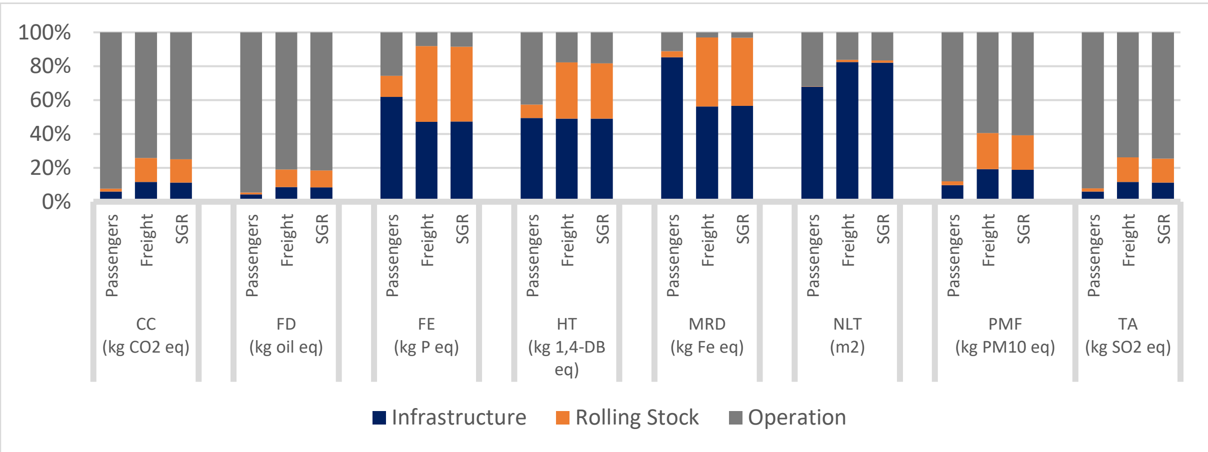

Figure 5.13 – Environmental impacts of the SGR-model allocated to passenger and freight transport

Table 5.12 and Table 5.13 report environmental impacts per passenger-kilometre and tonne-kilometre. These results will be useful to compare the SGR-model with previous research.

Table 5.12 – Environmental impacts of passenger transport in the SGR-model (per passenger-kilometre) over 60 years

Impact category	Unit	Infrastructure	Rolling Stock	Operation	Total
Climate change	kg CO2 eq/pkm	1.16E-03	3.13E-04	1.77E-02	1.92E-02
Fossil depletion	kg oil eq/pkm	2.75E-04	8.06E-05	6.14E-03	6.49E-03
Freshwater eutrophication	kg P eq/pkm	7.94E-07	1.60E-07	3.28E-07	1.28E-06
Human toxicity	kg 1,4-DB eq/pkm	1.26E-03	2.00E-04	1.08E-03	2.54E-03
Mineral resource depletion	kg Fe eq/pkm	9.92E-04	4.29E-05	1.29E-04	1.16E-03
Natural land transformation	m2/pkm	9.58E-06	3.10E-08	4.51E-06	1.41E-05
Particulate matter formation	kg PM10 eq/pkm	3.84E-06	9.18E-07	3.45E-05	3.93E-05
Terrestrial acidification	kg SO2 eq/pkm	5.73E-06	1.80E-06	8.70E-05	9.45E-05

Table 5.13 - Environmental impacts of freight transport in the SGR-model (per tonne-kilometre) over 60 years

Impact category	Unit	Infrastructure	Rolling Stock	Operation	Total
Climate change	kg CO2 eq/tkm	4.31E-03	5.32E-03	2.76E-02	3.72E-02
Fossil depletion	kg oil eq/tkm	1.02E-03	1.23E-03	9.53E-03	1.18E-02
Freshwater eutrophication	kg P eq/tkm	2.95E-06	2.79E-06	5.09E-07	6.25E-06
Human toxicity	kg 1,4-DB eq/tkm	4.67E-03	3.15E-03	1.68E-03	9.50E-03
Mineral resource depletion	kg Fe eq/tkm	3.69E-03	2.68E-03	2.00E-04	6.56E-03
Natural land transformation	m2/tkm	3.56E-05	5.38E-07	7.01E-06	4.32E-05
Particulate matter formation	kg PM10 eq/tkm	1.43E-05	1.57E-05	4.41E-05	7.41E-05
Terrestrial acidification	kg SO2 eq/tkm	2.13E-05	2.69E-05	1.35E-04	1.83E-04

5.3 Key findings

The results of the life cycle impact assessment provide insights about environmental impacts of the SGR-model.

It is apparent from these results that the key element to improve the global environmental performance of the SGR-model is to explore alternative sources of electricity production that could replace the use of fossil fuels (natural gas and oil) since operation phase is the most contributing subsystem to climate change, fossil depletion, particulate matter formation, and terrestrial acidification (4 out of 8 of selected impacts to study).

Environmental impacts from the infrastructure only were presented under three approaches: from the whole life cycle perspective, by analysing each railway component, and by analysing each section type.

When looking at the whole life cycle of the infrastructure, construction and maintenance stages present a balanced contribution to the environmental impacts except to natural land transformation. Indeed, construction has a larger contribution because building this new railway line requires to clear an extensive land area for the right-of-way. However, maintenance only includes maintenance of the track. Therefore, environmental impact estimations from maintenance phase are probably underestimated.

Materials have great contributions to environmental impacts of the infrastructure. Materials cover more than 95% of the freshwater eutrophication, human toxicity, and mineral resource depletion impacts. More specifically, steel (low-alloyed) is the most significant contributor overall. Transport which is responsible for diesel consumption but also requires vehicles and infrastructure is globally the second contributor (except to natural land transformation). Transport by lorry is found to have higher contributions than shipping transport. CO_2 emitted during vegetation clearance results in high contribution to climate change from the infrastructure, and land transformation from the railway line construction covers nearly the entire natural land transformation impact. Use of machinery, electricity, and excavation activities present a rather low contribution.

Among the various components forming the railway line, track and power and signalling system have the highest contributions to the environmental impacts except natural land transformation. A closer inspection at track components indicates that rails and transport of ballast are key contributors. Regarding power and signalling system, steel and copper present the highest contributions. Concrete and steel used to build tunnels, crossing structures, and culverts are the main sources of environmental impacts from these three components. However, electricity consumption during construction of tunnels is also a significant source of environmental impacts and is especially responsible for fossil depletion (22% contribution).

The SGR-model is mainly composed of open section (97.9% of the main line). Therefore, limiting the analysis of environmental impacts from a global perspective does not reveal the high impacts from tunnels and crossing structures & viaduct. As an example, on a metre basis, the climate change impact of tunnel section is up to more than 5 times the one of open section and more than 2 times the one of crossing structure section.

Surprising results were obtained regarding the rolling stock: goods wagons have a particularly high contribution. This could be explained by their short kilometric lifetime and intense use in the SGR-model.

Based on the key findings from the life cycle impact assessment, next chapter has the purpose to develop alternative scenario to explore how to reduce environmental impacts of the SGR-model and evaluate how sensitive environmental performance of the SGR-model is when introducing some changes in the model.

6 Alternative scenarios

Combining an LCA model with some scenarios has already been conducted in the literature such as in the studies of the HSR in Norway (Grossrieder, 2011), the HSR in China (Yue *et al.*, 2015), and the Mumbai suburban railway (Shinde *et al.*, 2018).

This chapter has the purpose to use the developed LCA model in a scenario-based framework to seek improvement of the environmental performance of the SGR-model.

6.1 Cleaner electricity

Based on the Ecoinvent v3.2 dataset for high-voltage electricity supply (Treyer, no date c), global warming potential of 1 kWh of electricity supplied in the SGR-model is of 658 gCO_2eq/kWh.

Among the main sources of electricity production in Tanzania (natural gas, hydropower and oil), oil is the electricity source which has the highest climate change impact per kWh and this is also the source which has the highest environmental impact value in 5 out of the 8 impact categories selected in this thesis as displayed in the graph in appendix (Appendix D1).

In the following sections, scenarios for a less carbon-intensive electricity production are developed to reduce the global warming potential per kWh of electricity supply mix in the SGR-model. These scenarios have the purpose to evaluate how changes in the electricity supply mix influence the environmental impacts of the operational phase and of the whole SGR-model.

6.1.1 Fossil fuel scenario

Replacing electricity produced from oil by other sources of electricity production is a first alternative. This idea is suggested in the ESIA report (ERM, 2019, p. 426) and in another article exploring electricity production scenarios in Tanzania (Rocco *et al.*, 2020).

According to scenarios of electricity development in the Power System Master Plan in Tanzania updated in 2016 (Power System Master Plan 2016 Update, 2016), coal will have a large contribution in the electricity production. For that reason, the first scenario consists of introducing electricity production from coal by replacing half of the electricity production from oil by coal and the other half, by natural gas.

6.1.2 Less coal scenario

Tanzania has potentials for renewable energies, especially for solar power production (Hermann, Miketa and Fichaux, 2014). The second scenario consists of introducing a lower share of coal-based electricity in the production mix and to produce electricity from solar and wind. Thus, half of the electricity production from oil is still replaced by natural gas, a quarter is replaced by coal and the last quarter, by both solar and wind power (50:50).

6.1.3 Renewables scenario

A third scenario is developed in which coal-based electricity is not introduced and the share of natural gas is also reduced in comparison with scenarios fossil fuel and less coal by increasing the share of electricity from solar power. Increasing the share of hydropower was excluded since Tanzania suffers from drought issues (Makoye, 2015).

Table 6.1 summarizes how oil-based electricity production is replaced by other sources of electricity in the three scenarios.

Table 6.1 – Composition of electricity generation sources replacing oil-based electricity production in the three scenarios

Scenario fossil fuel	Less coal scenario	Renewable only
50% coal 50% natural gas	50% natural gas 25% coal 12.5% wind 12.5% solar	25% natural gas 12.5% wind 62.5% solar

Figure 6.1 illustrates the electricity supply mix scenarios in comparison with the baseline scenario which corresponds to the electricity production dataset available in Ecoinvent database v3.2 (Treyer, no date c).

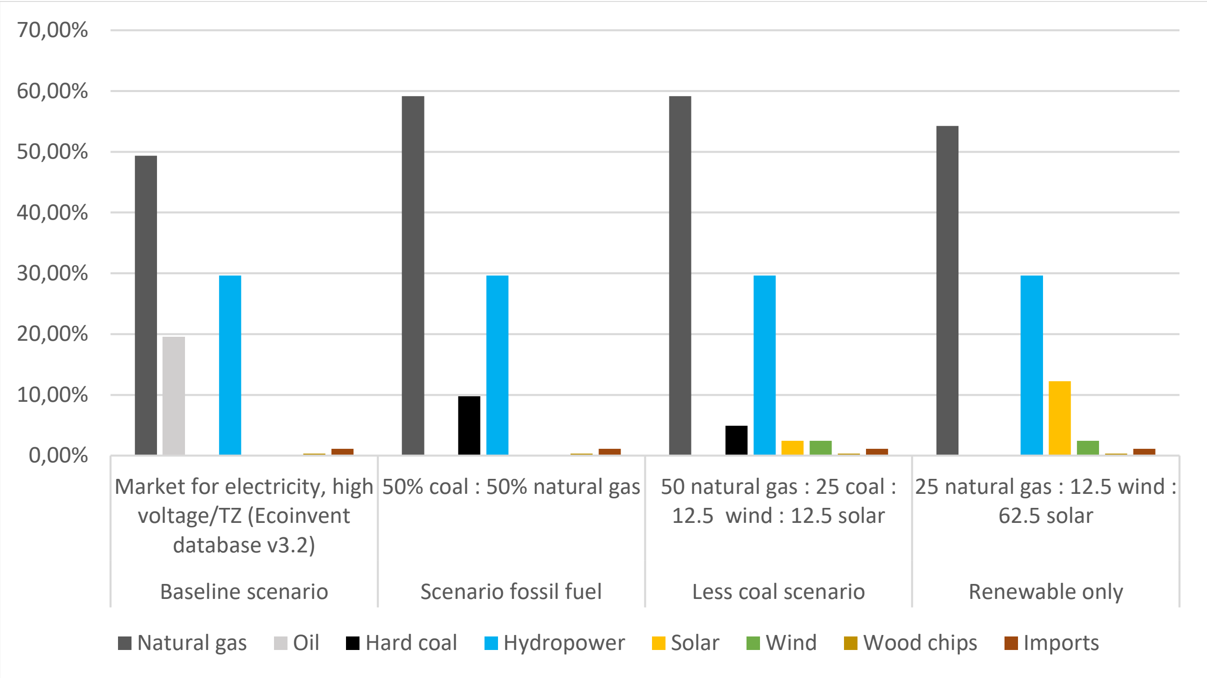

Figure 6.1 – Electricity supply mix scenarios

6.1.4 Environmental results

In order to implement the scenarios in Arda, the high voltage electricity production process from Ecoinvent v3.2 (Treyer, no date c) is modified accordingly to changes in the production mix and no change has been made regarding imports share in the supply mix.

However, the Ecoinvent database v3.2 (Wernet *et al.*, 2016) does not contain processes for electricity production at high voltage for solar and wind in Tanzania. It was then chosen to model the electricity production from solar power by using the process "electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted, TZ" (Treyer, no date a) and using the process of wind electricity production in South Africa "electricity, high voltage/electricity production, wind, 1-3MW turbine, onshore/ZA" (Treyer, no date b). These processes are assumed to be representative of electricity production from renewables in Tanzania.

Figure 6.2 provides the global warming impact results for 1 kWh of electricity produced by the different scenarios developed in the previous sections. From these results, it can be seen that replacing oil with other sources of electricity reduces the global warming impact per kWh and introducing renewables lead to a more important reduction.

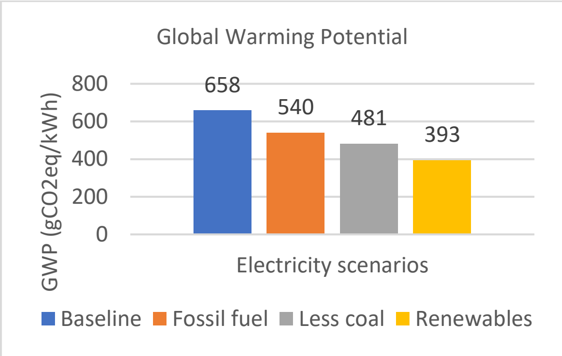

Figure 6.2 - Global Warming Potential of electricity supply scenarios per kWh electricity (gCO_2eq/kWh)

In appendix (Appendix D2), results per kWh electricity for all impact categories available in ReCiPe are compared with the baseline scenario.

Environmental impact changes are investigated for the whole SGR-model as depicted in Figure 6.3.

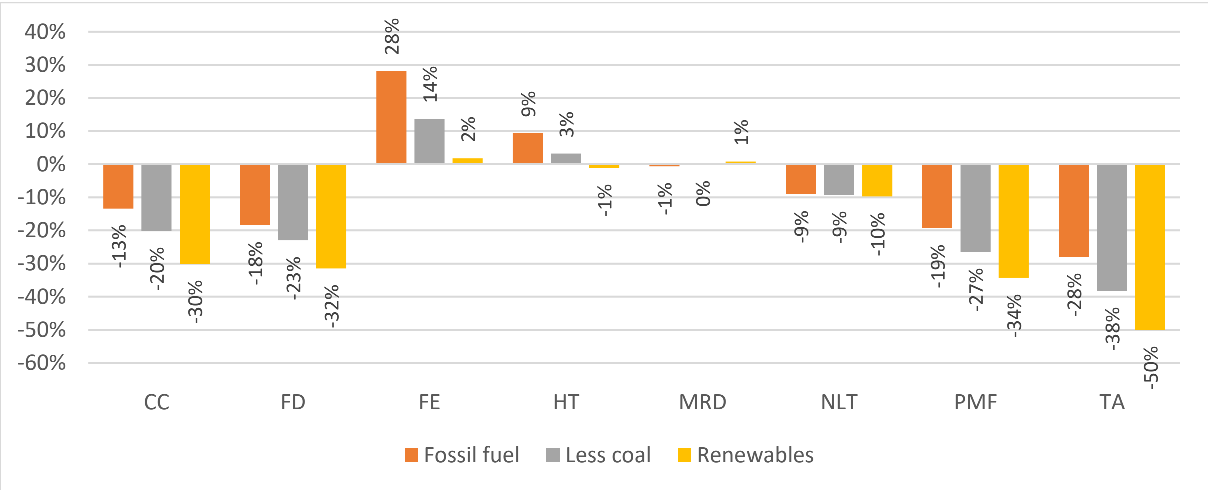

Figure 6.3 – Environmental impacts changes of the SGR-model for the three scenarios of electricity production

Increases in freshwater eutrophication and human toxicity impacts for the fossil fuel and less coal scenarios are observed. These increases come from the introduction of coal which is responsible for higher damages in these two impact categories than oil removed from the production mix.

It can be noticed that despite a visible increase in mineral resource depletion for the renewables scenario when looking at 1 kWh electricity (Appendix D2), almost no change is observable when looking at the whole SGR-model level. This can be explained by the low contribution of operation to the environmental impacts: in the baseline scenario, infrastructure and rolling stock cover about 97% of this impact and the increase induced by the introduction of renewables is not significant enough to be visible at the whole system level.

6.2 Material efficiency

Materials altogether have the highest contribution to environmental impacts from the infrastructure in the SGR-model. The Organization for Economic Co-operation and Development (OECD) emphasizes that the growth of materials use is not without consequences and all the life cycle activities related to materials (extraction, processing, use and disposal) have environmental impacts (OCDE, 2019). As shown in the previous chapter (Figure 5.3), the category materials is the first contributor to all impact categories except natural land transformation. It is therefore needed to investigate how environmental impacts related to the use of material resources can be reduced.

Material efficiency strategies such as more intensive use, product design improvement, material substitution, lifetime extension, and material reuse aim to reduce environmental impacts of production and processing (Allwood *et al.*, 2011). In this section, lifetime extension strategies are implemented as alternative scenarios.

6.2.1 Lifetime extension of rails, pads, and sleepers

In the baseline scenario, lifetime of rails, pads, and sleepers was estimated to be 25 years. In this scenario, it is assumed that these components can reach a lifetime of 30 years (+20% increase of lifetime) without altering material and energy requirements for their production. Table 6.2 provides the number of maintenance activities included in the baseline and the lifetime extension scenarios.

Table 6.2 – Maintenance activities considered in the baseline and the lifetime extension scenarios

Scenario	Rail renewal	Sleepers renewal	Fastenings renewal	Pads renewal	Ballast tamping	Ballast cleaning	Ballast renewal
Baseline	1.4	1.4	2	1.4	15	3	2
Lifetime extension	1	1	2	1	15	3	2

This scenario results in a full accounting of maintenance activities for rails, pads, and sleepers since at year 60, these components reach the end of their service life.

Figure 6.4 illustrates how environmental impacts of the whole SGR-model change when lifetime of rails, pads and sleepers is extended from 25 years to 30 years.

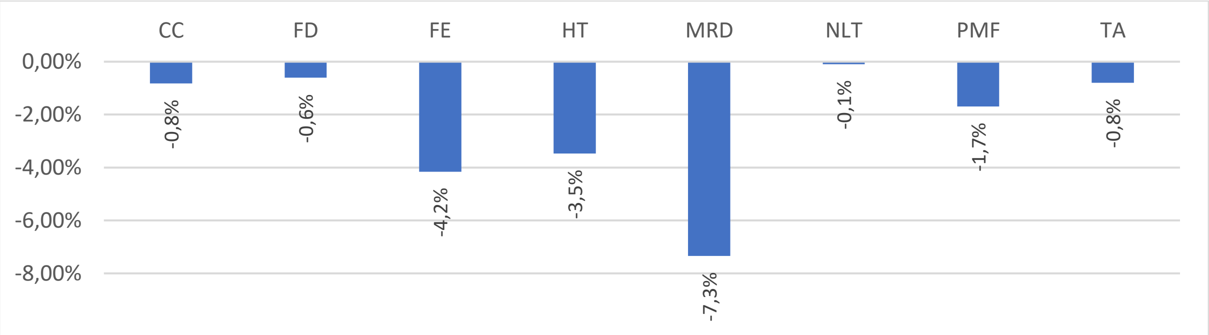

Figure 6.4 – Environmental impacts changes of SGR-model resulting from lifetime extension of rails, pads, and sleepers

Mineral resource depletion is the impact category where the decrease is the highest, about 7.3% decrease. This result is in line with a reduced use of steel (low-alloyed) from lifetime extensions of rails and sleepers since steel contribution to mineral resource depletion of the SGR-model infrastructure is of 85% in the baseline scenario. Reduction by 4.2% and 3.5% are also observed in freshwater eutrophication and human toxicity.

6.2.2 Lifetime extension of goods wagons

In previous chapter, it was mentioned that goods wagons had a high contribution to the environmental impacts of the SGR-model.

In a study about the proposed high-speed railway line Europabanan in Sweden, Åkerman (2011) reports that 30.1 million tkm are performed during the life of a goods wagon. Based on the estimated number of goods wagons needed for the SGR-model (17019.34 goods wagons) and the total transport volume of goods over the whole life cycle of the SGR (4.19E+11 tkm), the transport volume can be estimated to 24.6 million tkm/goods wagon. This value is about 18% lower than the value reported by Åkerman (2011) for Swedish goods wagons.

In this section, it is therefore decided to increase the lifetime in kilometres of goods wagons in the SGR-model to reach 30.1 million tkm performed per goods wagon. This leads to increase the lifetime in kilometres by about 22%.

Figure 6.5 illustrates environmental impacts changes of the whole SGR-model.

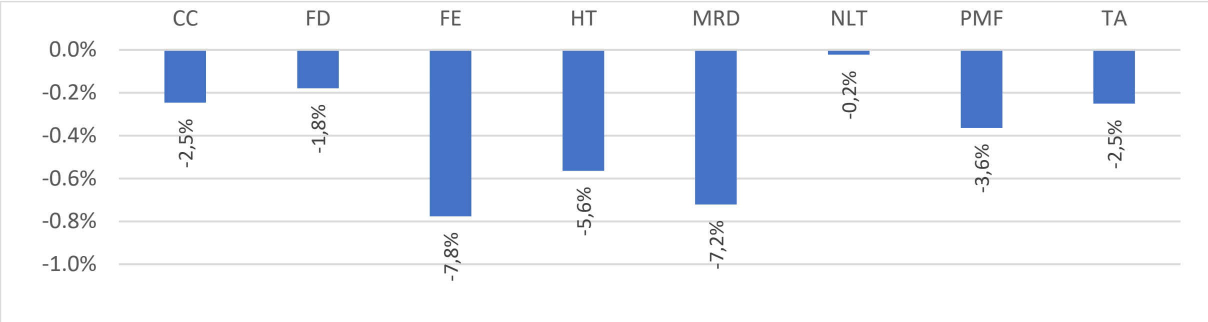

Figure 6.5 - Environmental impacts changes of SGR-model resulting from lifetime extension of goods wagons

The largest improvements from extending kilometric lifetime of goods wagons are observed in freshwater eutrophication (7.8% reduction), in human toxicity (5.6% reduction), and in mineral resource depletion (7.2% reduction). Goods wagons are mainly manufactured from steel and aluminium (Spielmann, no date a; Spielmann *et al.*, 2007). Increasing their kilometric lifetime leads to a lower number of goods wagons needed to satisfy the expected freight load to transport per year. Therefore, this results in lower quantities of materials particularly affecting these impact categories.

6.3 Secondary steel

Another alternative to improve environmental performances of the SGR-model is to introduce the use of recycled materials. Recycling processes are identified as energy efficiency strategies by Allwood *et al.* (2011). In the SGR-model, steel (low-alloyed) has been modelled as primary steel. Therefore, in this section, secondary steel (low-alloyed) is introduced in the production of rails and sleepers. It is assumed that for future replacements of these components in the maintenance phase, technological improvements lead to the possibility to use secondary steel in rails and sleepers manufacturing without modifying the rest of their materials and energy inventory.

In Ecoinvent database, the production of primary steel takes place in a converter and secondary steel in an electric arc furnace (Althaus and Classen, 2005). To model the use of secondary steel, a mix of these two processes is created. Figure 6.6 presents the environmental impacts changes of the SGR-model for three scenarios of rails and sleepers' production during maintenance phase: use of 20%, 50% and 100% secondary steel low-alloyed to replace primary steel low-alloyed.

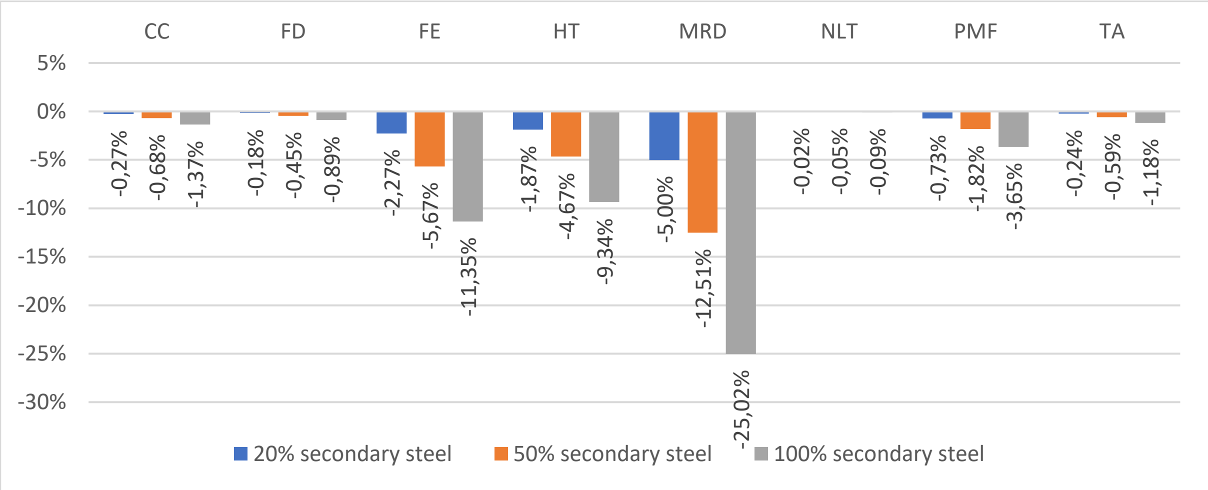

Figure 6.6 - Environmental impacts changes of SGR-model resulting from the use of secondary steel to produce rails and sleepers in the maintenance phase

The use of secondary steel results globally in reduction of all environmental impacts of the SGR-model. The largest impact reductions are reductions of mineral resource depletion, but also in freshwater eutrophication, human toxicity, and to a lesser extent in particulate matter formation. Climate change, fossil depletion, natural land transformation, and terrestrial acidification are almost not affected.

6.4 Transportation

Based on the life cycle impact assessment results, one additional scenario is developed. Indeed, transportation of materials, especially road transport, has a high contribution to the environmental impacts of the infrastructure. However, transport distances are based on rough estimations. A scenario is developed to investigate how sensitive the environmental impacts are when transportation distances are changed. Figure 6.7 presents environmental impacts changes when transport distances are decreased by 10%.

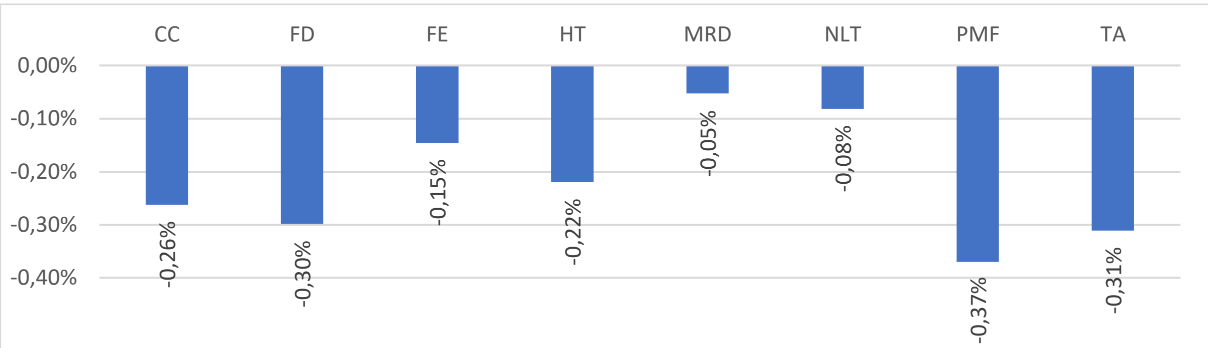

Figure 6.7 - Environmental impacts changes of SGR-model resulting from 10% decrease of transportation distances

Globally, environmental impacts of the SGR-model undergo rather low decreases. Particulate matter formation is the most affected impact, but the decrease is of only 0.37%.

6.5 Overview

All environmental impacts changes resulting from the scenarios developed in the previous sections are reported in Figure 6.8.

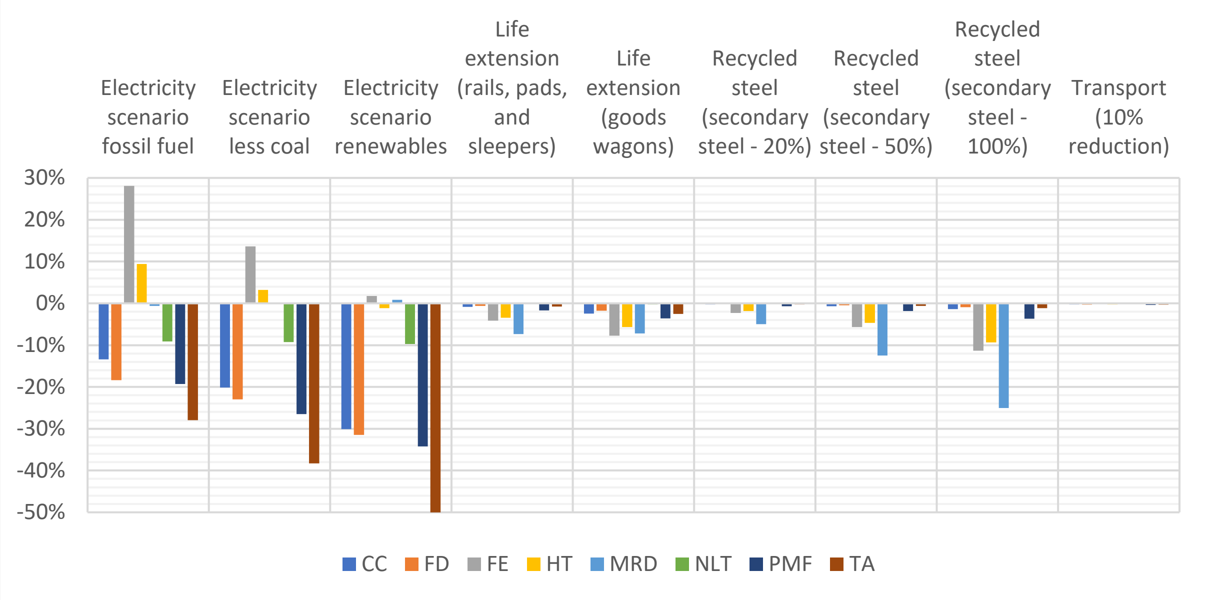

Figure 6.8 – Overview of scenarios results

Each scenario affects differently the environmental performance of the SGR-model.

- Climate change, fossil depletion, natural land transformation, particulate matter formation, and terrestrial acidification are more affected by electricity scenarios. Natural land transformation undergoes a similar decrease for the three electricity scenarios while higher decreases are observed for the other impact categories in the RE scenario.
- Freshwater eutrophication, human toxicity, and mineral resource depletion are more affected by use of 100% of secondary steel during the maintenance phase. Nevertheless, these impacts are also influenced by life extension of railway components and goods wagons.
- Transport scenario results are not visible on the graph due to the low impact reduction they induce.

The only scenarios leading to increases in specific impacts are scenarios with changes in the electricity mix. The impacts increased for these scenarios are freshwater eutrophication, human toxicity, and mineral resource depletion. However, one way to discuss the importance of impact categories is to look at the endpoint indicators from ReCiPe (Goedkoop *et al.*, 2013).

Freshwater eutrophication is included in the calculation of the endpoint Ecosystem. However, climate change is also included in the calculation of this endpoint. There are two other impact categories whose values are also increasing: freshwater ecotoxicity and marine ecotoxicity as depicted in the LCIA of 1kWh of electricity for the three scenarios presented in appendix (Appendix D2). Based on their respective conversion factors[13] and their resulting contributions to the endpoint, the decrease in climate change impact from changes in the supply electricity mix outbalances the increase in the three impact categories.

Human toxicity is included in the calculation of the endpoint Human health. Based on the same approach as for the endpoint Ecosystem, the decrease in climate change impact outbalances the increase in human toxicity.

Regarding mineral resource depletion, included in the calculation of the endpoint Resources, its increase is outbalanced by the decrease in fossil depletion.

A table summarizing the contribution of impacts discussed above to the three endpoint indicators is available in appendix (Appendix D3).

[13] Available in the Excel spreadsheet from the ReCiPe impact assessment method version 1.11 (Goedkoop *et al.*, 2013, 2014).

7 Discussion

Chapter 5 presented the life cycle impact assessment of the SGR-model and Chapter 6 introduced the development of a few alternative scenarios. Several impact categories are included in the analysis. This offers a broad overview of the environmental performance of the SGR-model. However, the model was built on many assumptions and estimates. The model itself needs to be discussed as well as the results generated in the life cycle impact assessment.

The first section of this chapter presents why it is interesting to analyse several impact categories. The second section is meant to compare the results with previous research. The third section has the purpose to discuss why this railway line was chosen to study environmental impacts of railway development, the model itself as well as data quality.

7.1 Environmental impact categories

Including several impact categories in the life cycle impact assessment gives a broad picture of the environmental performance of the SGR-model. This aspect is discussed based on Figure 7.1.

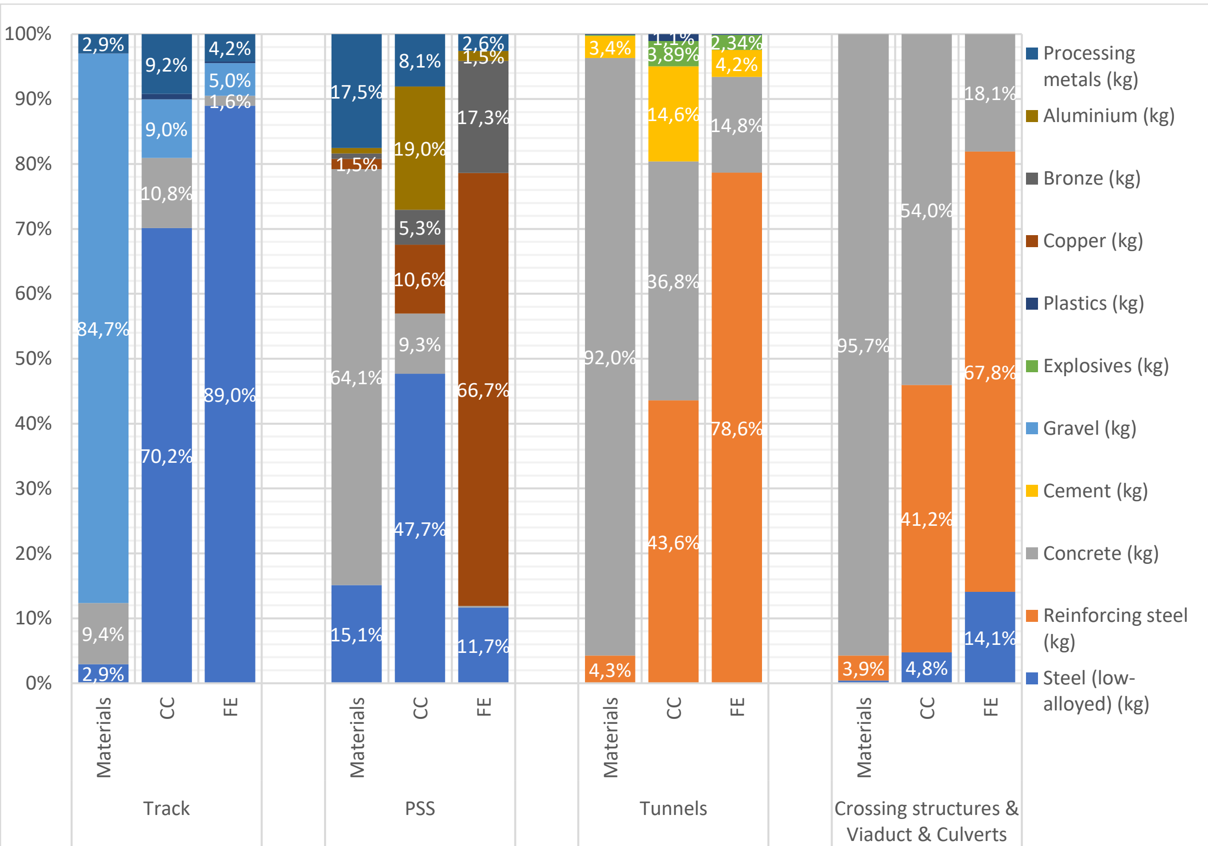

Figure 7.1 – Comparison of material composition, climate change, and freshwater eutrophication for railway components at the construction stage of the SGR-model. (Only labels for values above 1% are displayed on the graph).

In the figure above, railway components (crossing structures, viaduct, and culverts are grouped together) are presented from three different perspectives: their material composition, climate change impact, and freshwater eutrophication impact of these materials (only materials have been included since they can be compared based on their quantities in kilogrammes).

When observing the material composition of track, one may see that ballast represents nearly 85% of materials quantities. Regarding power and signalling system, tunnels, and crossing structures and culverts, concrete is the material in largest quantity. However, when comparing with the environmental impacts, it is possible to see that steel (low-alloyed) dominates climate change of track and PSS. The contribution of steel (low-alloyed) to freshwater eutrophication is even higher for track, but for PSS, copper is the most contributing material. Regarding tunnels, crossing structures and culverts, climate change and freshwater eutrophication present two different contribution results: reinforcing steel has a higher contribution in freshwater eutrophication than in climate change.

Dealing with a high load of environmental impact results is a challenging task. In this thesis were prioritized the impact categories with a high contribution to the endpoint indicators. However, it is also important to understand where the impact of a specific input comes from. The high contribution of copper in the freshwater eutrophication impact can be explained by investigating the background process chosen to represent copper in the SGR-model "copper production, primary, RoW" (Classen, no date). Analysing the freshwater eutrophication impact for 1 kg of copper with Arda reveals that more than 98% of the impact comes from the "treatment of sulfidic tailing, off-site, GLO". This waste treatment is also responsible for more than 69% of human toxicity impact from copper, nearly 60% of freshwater eutrophication impact from steel (low-alloyed), and 77% of its human toxicity impact.

When investigating, climate change impact with Arda from 1 kg of steel (low-alloyed) and 1 kg of concrete (high exacting requirements), pig iron and clinker production are their respective most contributing activity. About 32% of climate change impact from steel comes from "pig iron production, GLO", and about 73% of climate change impact from concrete comes from "clinker production".

Using Arda to evaluate the impact of 1 unit of a specific input, it is possible to investigate more specifically which background processes and stressors have the highest contributions to its environmental impacts. This investigation provides a better understanding of impacts of an input of material or energy. This can be useful to investigate alternative inputs or discuss how to improve the environmental performance of this specific input and thus the global environmental performance of the system.

Including several impact categories allows to see that it is not the same background process or stressor which contribute the most to the environmental impact. If one would only study one impact category, these findings would not be observed and this could lead to problem shifting (Rosenbaum *et al.*, 2018).

7.2 Comparison to previous research

The SGR-model has been built using several sources of data and assumptions. Therefore, a comparison of the results to previous research is established to assess the validity of this model.

7.2.1 Climate change per transport unit

Climate change impact from passenger transport of the SGR-model is first compared per passenger-kilometre. Figure 7.2 and Figure 7.3 present the comparison of the SGR-model with the suburban railway in Mumbai (Shinde *et al.*, 2018), the Ecoinvent process "transport, passenger train, long-distance, CH" (Spielmann, no date g), the Bothnia Line (Stripple and Uppenberg, 2010), the HSR Beijing-Shanghai (Yue *et al.*, 2015), and the Follo Line (MiSA AS, 2011).

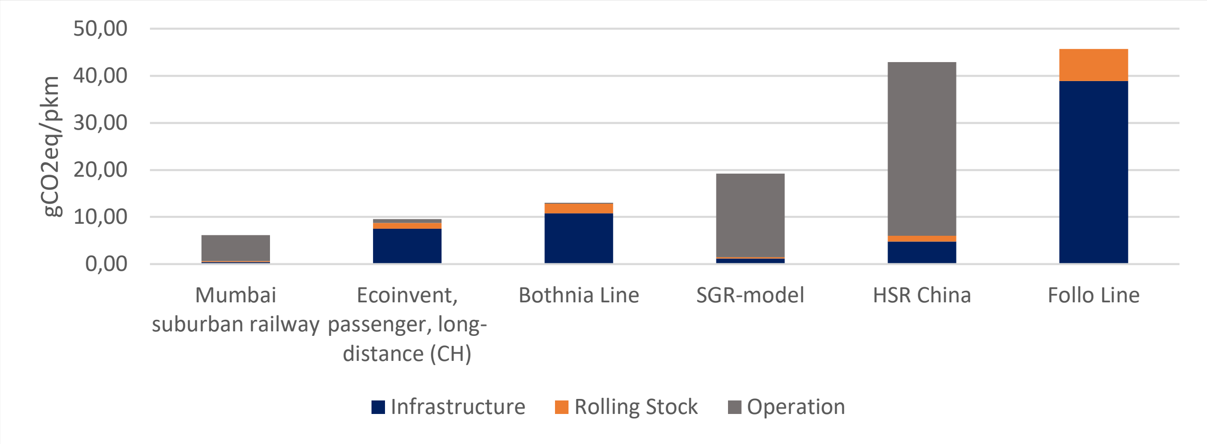

Figure 7.2 – Comparison of climate change (gCO_2eq/pkm) of the SGR-model (passenger transport) to previous research (the operation of the Follo Line is included in the infrastructure and the rolling stock).

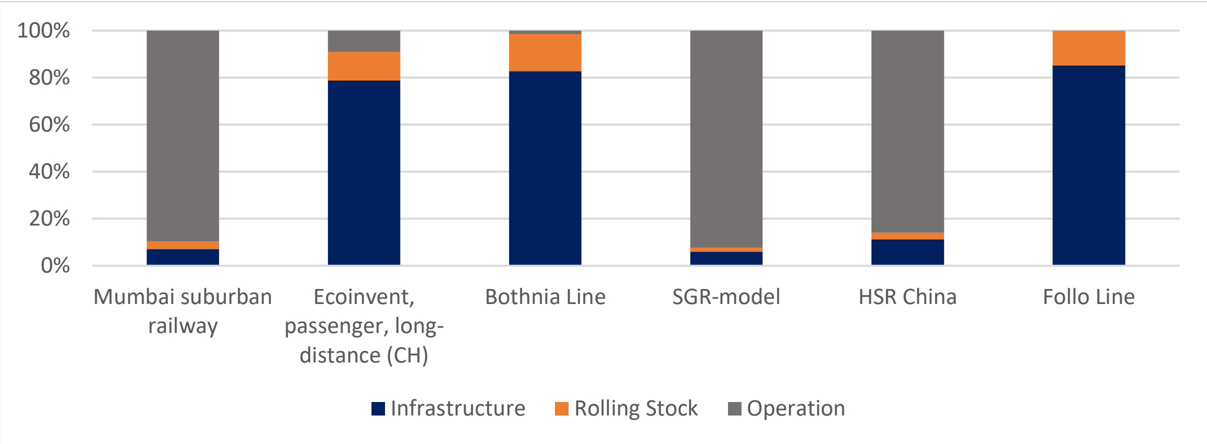

Figure 7.3 - Comparison of relative contribution of each subsystem to climate change of the SGR-model (passenger transport) and previous research (the operation of the Follo Line is included in the infrastructure and the rolling stock).

Some observations can be extracted from the two figures:

- The climate change impact per pkm from the SGR-model is in the range of values from selected previous studies.
- The contribution of each subsystem (infrastructure, rolling stock, and operation) presents a pattern similar to the one for Mumbai Suburban and HSR in China. This contribution pattern, for which operation dominates, is different from Scandinavian countries and Switzerland (Ecoinvent), where the electricity has low carbon intensity and where infrastructure has the highest contribution. Moreover, for these three railway lines, the ratio of bridges and tunnels is higher than the one in the SGR-model. About 90% of the Follo Line is a tunnel section (MiSA AS,

2011), tunnels and bridges represent about 17% of the Bothnia Line's track length (Stripple and Uppenberg, 2010), and in Ecoinvent, the railway track model includes 3% of bridges and 7% tunnels (Spielmann *et al.*, 2007)) while the bridges and tunnels represent only 2.1% of the SGR-model's route length.

Some differences in scopes from the various studies must be highlighted. The study of HSR in China only includes the construction phase of the infrastructure (Yue *et al.*, 2015) while all the other studies include the maintenance phase and some include the disposal phase. Moreover, not all the same components are included in the infrastructure subsystem. For example, only the track, power supply system, platforms, and foot over bridges are considered in the Mumbai suburban railway infrastructure (Shinde *et al.*, 2018) while larger system boundaries are considered for the Bothnia Line including for example track foundations and passenger stations (Stripple and Uppenberg, 2010).

The operation subsystem may also present some differences. Operation of the Mumbai suburban railway and the Bothnia Line include both rail vehicles and infrastructure operations (Stripple and Uppenberg, 2010; Shinde *et al.*, 2018). Operation of the infrastructure in the Ecoinvent process is directly included in the infrastructure process (Spielmann *et al.*, 2007), and operation of Follo Line is directly allocated to the respective infrastructure and rolling stock subsystems. Regarding the SGR-model, operation is only operation of the rolling stock since no operation for the infrastructure was considered.

Climate change impact from freight transport of the SGR-model is then compared per tonne-kilometre. Figure 7.4 and Figure 7.5 present the comparison of the SGR-model with the Bothnia Line (Stripple and Uppenberg, 2010), the Follo Line (MiSA AS, 2011), the Ecoinvent process "transport, freight train, electricity, RoW" (Gindroz, no date b), and the freight rail transport in Belgium (Merchan, 2019).

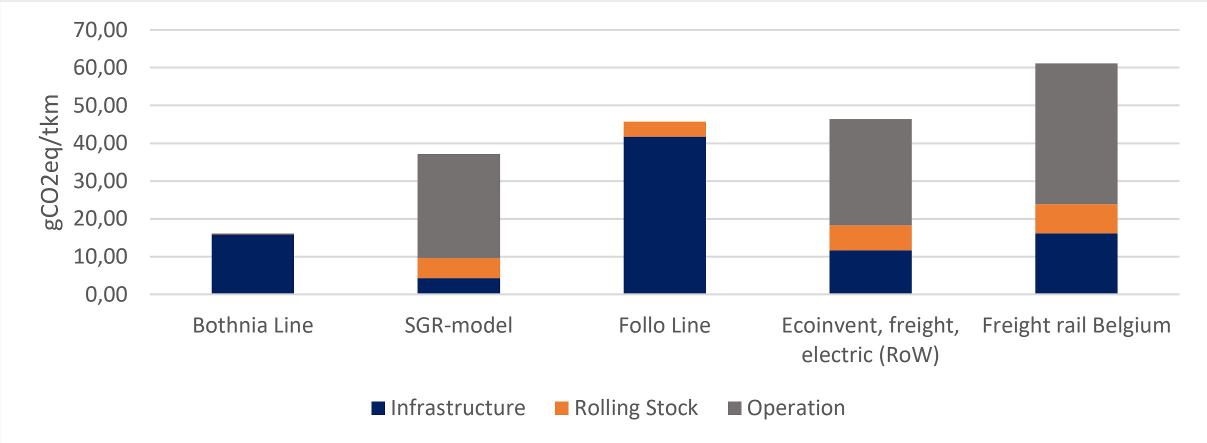

Figure 7.4 - Comparison of climate change (gCO_2eq/tkm) of the SGR-model (freight transport) to previous research (the operation of the Follo Line is included in the infrastructure and the rolling stock).

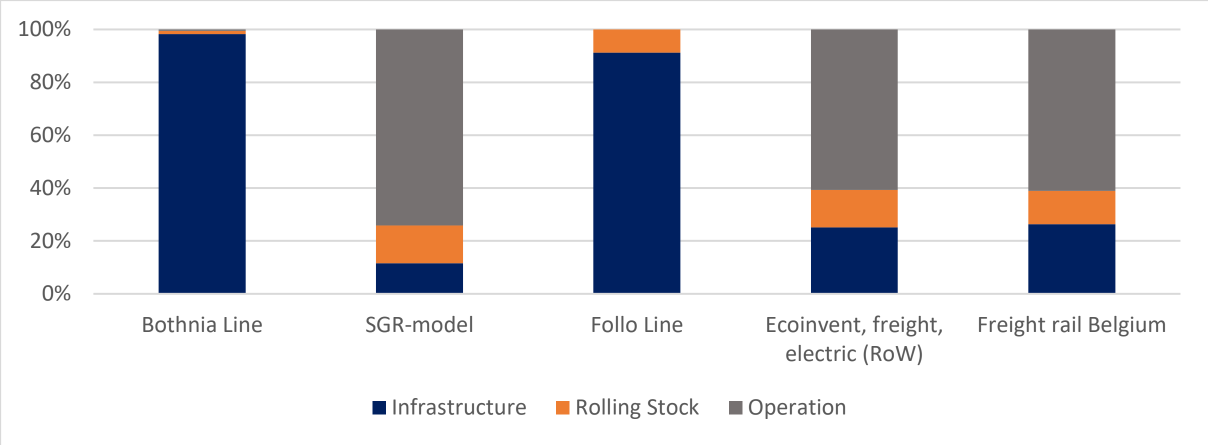

Figure 7.5 - Comparison of relative contribution of each subsystem to climate change of the SGR-model (freight transport) and previous research (the operation of the Follo Line is included in the infrastructure and the rolling stock).

As for passenger transport, some observations can be extracted from the two figures:

- The climate change impact per tkm from the SGR-model is in the range of values from selected previous studies.
- The contribution of each subsystem (infrastructure, rolling stock, and operation) presents a pattern similar to the one for Ecoinvent and Belgium. As for passenger transport, same observations can be done for Scandinavian railway lines. A low contribution of infrastructure in the SGR-model is again explained by the low ratio of bridges and tunnels.

Regarding scope differences, the operation of the infrastructure included in the infrastructure subsystem for both the Follo Line and the Belgium rail network.

One difference can also be noticed when comparing contribution of each subsystem to the global impact: rolling stock of the Bothnia Line presents a lower contribution to the climate change impact of freight transport than passenger transport. This point was highlighted in the study and emphasized that freight transport "is more vehicle efficient" (Stripple and Uppenberg, 2010, p. 162). However, the opposite is observed for the SGR-model. Indeed, the ratio tonne vehicle per passenger is of 0.42 tonne/passenger while the ratio tonne vehicle per tonne of goods is of 0.86 tonne/tonne of goods. This difference is explained by the way the rolling stock is modelled and this necessarily influences environmental conclusions.

Even if climate change impact per pkm and per tkm in the SGR-model are in the range of impacts estimated in previous studies, it is important to be cautious when comparing results since various scopes are considered. However, this comparison is still interesting to check the order of magnitude of the results and the coherence with previous research.

7.2.2 Environmental impacts of infrastructure

In this section, climate change impact from infrastructure of several railway studies is compared with the impact from the infrastructure modelled in the SGR-model. Studies selected for this comparison are studies for which it is possible to calculate climate change impact of single-track per (metre*year). In addition, studies using the Ecoinvent process to model infrastructure are avoided.

Climate change impact of the SGR-model infrastructure is then compared with the HSR Tours-Bordeaux (de Bortoli, Bouhaya and Feraille, 2020), Mumbai suburban railway (Shinde *et al.*, 2018), Ecoinvent processes "railway track construction" in Switzerland (CH) and in the rest of the world (RoW) (Spielmann, no date d, no date c), and the Bothnia Line (Stripple and Uppenberg, 2010). Climate change impacts from Mumbai suburban railway and the Bothnia have been calculated per (metre*year) based on the calculation period considered and length of tracks in both studies.

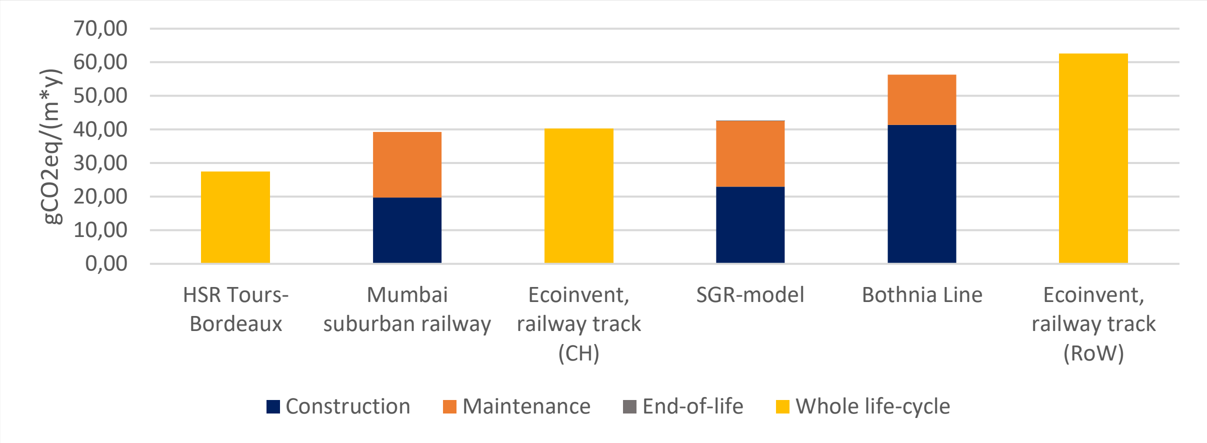

Figure 7.6 - Comparison of climate change (gCO$_2$eq/(m*year)) of the SGR-model infrastructure to previous research

Climate change impact per (metre*year) of the SGR-model infrastructure is in the range of impacts from previous research. In addition to the differences in scope highlighted in section 7.2.1, some differences in modelling choices can also be highlighted. In HSR Tours-Bordeaux, construction, maintenance, and end-of-life are included within the system boundaries. However, credits for recycling are granted and therefore leads to reducing the impact from the infrastructure (de Bortoli, Bouhaya and Feraille, 2020).

In the LCIA of the SGR-model, several impact categories have been included. Not all environmental studies of railway analyse several impact categories, or results are not always made available. Therefore, to compare the other impact results of the SGR-model, a comparison with Ecoinvent processes is presented in Figure 7.7. The impacts of the Ecoinvent processes have been divided by 2 since their inventory of materials and energy refers to a double-track.

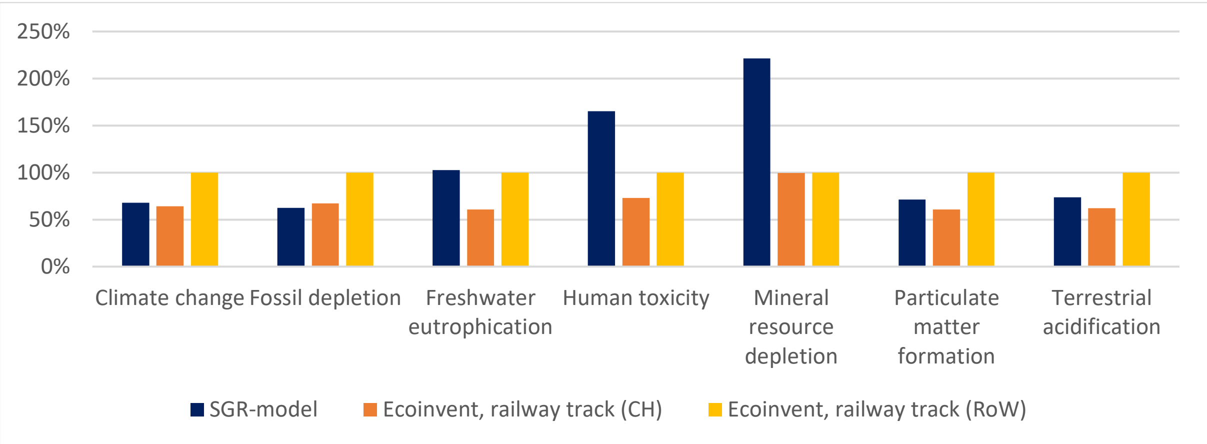

Figure 7.7 - Comparison of environmental impacts of the SGR-model infrastructure to Ecoinvent processes per single-track (metre*year)

Based on the report describing how railway track in Ecoinvent was modelled (Spielmann *et al.*, 2007), some thoughts are gathered below to try to explain the differences observed:

- Ecoinvent considers a lifetime of 100 years for the infrastructure, while the SGR-model impact is evaluated over 60 years (and assumes that lifetime of crossing structure, viaduct, and tunnels is of 60 years).
- Ecoinvent processes include activities which have not been considered in the SGR-model such as the use of lubricates and herbicides, while the SGR-model includes railway components not included in Ecoinvent processes such signalling infrastructure.
- Material chosen to represent rail production in the Ecoinvent processes is "market for reinforcing steel, GLO" while in the SGR-model, "steel production, converter, low-alloyed, RoW" was selected. This choice could be one reason explaining why the SGR-model has higher impacts in freshwater eutrophication, human toxicity, and mineral resource depletion since low-alloyed steel has higher impact per unit produced.

The impact natural land transformation was removed from the graph because the impact of the SGR-model is about 15 times as high as the one from Ecoinvent, railway track (RoW). A large area for the right-of-way was assumed to be transformed in the SGR-model, about 1.14 m^2/(metre*year) (considering a 60-year period of calculation) while in the Ecoinvent processes, the estimate is about 0.05 m^2/(metre*year) (Spielmann *et al.*, 2007). This discrepancy could be explained by the uncertainty of the estimate in the SGR-model and that the estimates are for two different regions (Switzerland for Ecoinvent and Tanzania for the SGR-model). Moreover, it is also unclear how the estimate from the Ecoinvent process has been calculated.

One last comparison is performed as part of the discussion about the validity of the SGR-model: the environmental impacts from tunnels. In the SGR-model, the inventory of materials and energy for the construction of tunnels was built using screenshots of videos to estimate the profile dimensions, comparing with previous knowledge, and making assumptions. Climate change impact per metre of tunnel from the SGR-model (only tunnel construction without track and power and signalling system) are compared to previous research in Figure 7.8 and Table 7.1.

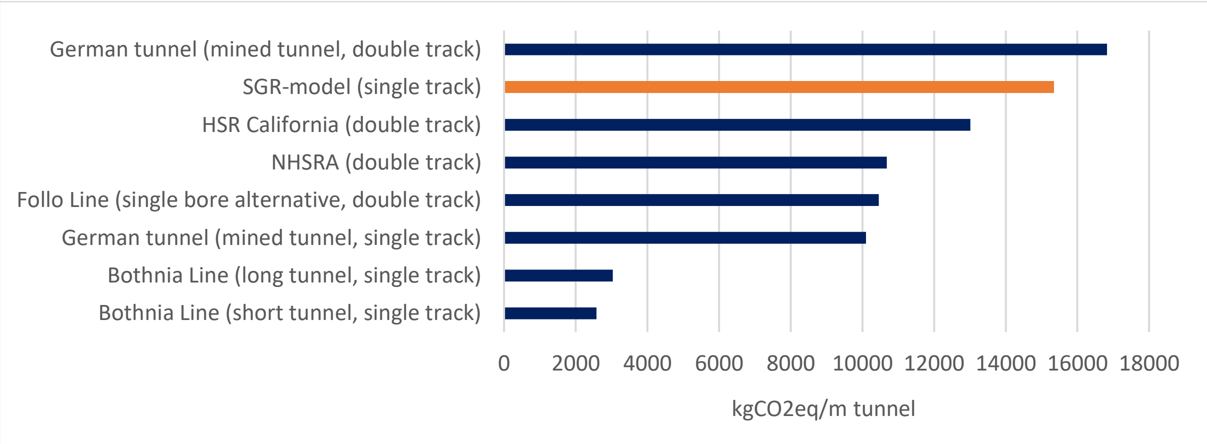

Figure 7.8 - Comparison of climate change (gCO_2eq/m) of the SGR-model tunnels to previous research

Table 7.1 - Comparison of climate change (gCO_2eq/m) of the SGR-model tunnels to previous research

	Bothnia Line (short tunnel, single-track)	Bothnia Line (long tunnel, single-track)	German tunnel (mined tunnel, single-track)	Follo Line (double-track)	NHSRA (double-track)	HSR California (double-track)	SGR-model (single-track)	German tunnel (mined tunnel, double-track)
$kgCO_2eq/m$	2577	3034	10,098	10,455	10,682	13,016	15,339	16,830
Source	(Stripple and Uppenberg, 2010)		(Schmied and Mottschall, 2013)	(Asplan Viak AS, 2011)	(Bergsdal *et al.*, 2012)	(Chang and Kendall, 2011)		(Schmied and Mottschall, 2013)

Based on this comparison, one may notice that climate change impact from tunnels in the SGR-model correspond to the upper range of the collected impacts. However, considering the estimated amounts of materials, especially steel and concrete, the result is not too surprising. Estimates have been calculated without considering that applying layers of concrete would reduce the arc length to estimate volume of additional layers. Electricity and cement quantities were taken from the inventory of the Follo Line tunnel, but cement quantity, which is rather high, is actually questioned in the study of HSR in Norway (Bergsdal *et al.*, 2012).

Based on the comparison to other studies, it appears that there is an overestimation of the climate change impact. However, since no data are available, it is not possible to confirm this overestimation. Most of the previous studies are based upon European cases. This regional difference certainly affects the impact value (for example, electricity production emits different quantities of GHG emissions).

In total, tunnels have a length of only 2.6 km (value which seems to be rather certain) for a route length of 541 km. This is therefore 0.5% of the railway line. Still, tunnels represent 2.2% of the infrastructure climate change impact. Although 2.2% seems to be a low value, it is significant considering the tunnels/railway line lengths ratio (0.5%). This could become interesting to study if the other sections of the SGR are planned to have more tunnels.

7.2.3 Challenges

Comparing life cycle environmental impacts of the SGR-model highlights some challenges. When results presented in previous research are aggregated or presented in the form of 100% stacked bar charts, it can be difficult to disaggregate them to get specific impact for a subsystem or a component.

Even if there are standards providing guidelines to perform a life cycle assessment, it is challenging to compare results from one study to another. Olugbenga, Kalyviotis, and Saxe (2019) emphasize the heterogeneity of railway embodied GHG emissions reported in studies based on a life cycle assessment methodology. Embodied GHG emissions results of a railway project are not only influenced by its own characteristics but also by the modelling choices made when performing the life cycle assessment (Olugbenga, Kalyviotis and Saxe, 2019).

7.3 The SGR-model

Before discussing the SGR-model itself and limitations of this model, some motivations leading to the study of the SGR are given.

7.3.1 Why this railway line?

The first step of this thesis was to choose a prospective or existing railway development to evaluate from an environmental life cycle perspective. The requirement was to find a railway line for which a minimum amount of information and data were available online.

Communication around the SGR in Tanzania was the first reason for choosing this railway line. The ESIA report is made available online and there is a clear will to provide information about the SGR to the public and stakeholders (ERM, 2019; Vogelsberger and Militschenko, 2019). A great number of videos are published on YouTube (TRC RELI TV, no date; Yapı Merkezi Tanzania, no date), the railway company in Tanzania provides a description of the project on its website (TRC, no date a), and there is even a Twitter account updated regularly (SGR_tz, no date). Despite not providing directly all the qualitative data necessary to build a model to analyse, these sources were valuable and helped visualizing and understanding the construction of the new railway infrastructure. In a way, this made up for the impossibility to carry field observations. However, the language was a barrier to a complete understanding.

The second reason motivating this choice is that studying the SGR using LCA methodology is a contribution to its global environmental analysis. As pointed out in the ESIA report, GHG emissions from the SGR can be direct and indirect GHG emissions, and more specifically, the ESIA report refers to the three scopes to classify GHG emissions (ERM, 2019, p. 413). Scope 1 accounts for direct GHG emissions, scope 2 for indirect GHG emissions related to electricity production, and scope 3 comprise all other indirect GHG emissions resulting from activities linked to the studied system (Ranganathan *et al.*, 2004, p. 25). The ESIA report provides an estimation of GHG emissions of scope 1 and scope 2, but not GHG emissions of scope 3. The LCA methodology, assessing emissions from a life cycle perspective, is therefore a way to include indirect emissions into the environmental assessment of the SGR.

The third reason for choosing the SGR as a railway to study is that only sections 1 and 2 are currently under construction, but other sections are planned to be built in the future. Environmental assessment of the SGR-model is part of the understanding of key elements contributing to environmental impacts. Hence, these results could be considered when making design choices for the rest of the line.

7.3.2 Limitations and strengths

One of the main challenges when doing the LCA of the SGR in Tanzania was to build the life cycle inventory for the foreground processes. Quantifying the quantities of materials and energy was not an easy task, especially when information available is sometimes not coherent from one source to another. These incoherencies are understandable considering that the railway line is still under construction. However, even if the line were already built and in operation, there would be no guarantee to find project-specific data easily available online.

7.3.2.1 Infrastructure in the SGR-model

When it came to decide which railway components to include in the model, some had to be excluded such as passenger stations, platforms, or maintenance sites. Trying to model these components would probably have led to a high uncertainty, especially that the Dar Es Salaam passenger station seems to be an all-glass building as shown on a video at 0min24 (Yapı Merkezi Tanzania, 2020b). However, including these components would increase the quantities of steel and concrete to build the stations, and electricity consumption when including their energy consumption.

Modelling land use and vegetation clearance was considered as a relevant element to include. Results indicate that about 11% of climate change impact of infrastructure is due to CO_2 emissions resulting from vegetation clearance. However, this result has a high uncertainty coming from the land cover description itself (Google Earth imagery was used by ERM (ERM, 2019, p. 290)) and from the carbon stock values which are derived from national level data (Mauya *et al.*, 2019). The calculated value differs from the one estimated in the ESIA report. The way it has been estimated in the ESIA report is based on assumptions and mentions that land use is not precisely determined (ERM, 2019, p. 416), while another section of the report details land use cover and has been used in this thesis (ERM, 2019, pp. 290–292). This reveals an incoherence in the report which would benefit from clarifications.

Earthwork activities were also modelled in a simple way trying to adjust available data. Doing it this way might induce double counting of excavated materials since additional excavation was also considered for tunnels, crossing structures, and viaduct.

Another aspect to discuss is the assumption regarding the 60-year period of calculation. Impacts resulting from construction of crossing structures, viaduct, and tunnels were fully accounted. It is as if after 60 years, these components have reached their end-of-life. To get around this issue, one may consider that after 60 years, a high-level maintenance is required.

Maintenance activities have been calculated based on lifetime in MGT reported in 2007 (Lichtberger, 2007). Based on calculations some maintenance activities would not happen at the same time while it would make more sense that fastenings are renewed at the same time as rail or sleeper renewal. Maintenance was also assumed to be the same all along the track while the use of track is probably different between the main line and sidings. Moreover, maintenance activities are also dependent on several parameters such as climate conditions as mentioned in section 4.4.2, and therefore these activities would probably be different from railway activities in Europe. Getting planned maintenance data as well as specific service lifetime for railway components used to build the SGR would improve the estimations of material and energy requirements, and therefore estimations of maintenance phase environmental impacts.

In the SGR-model, the end-of-life was modelled considering an allocation cut-off for recycling and assuming that, in the future, recycling will be the main end-of-life fate for railway components. This recycling assumption leads to low impacts from end-of-life. Without this assumption, transport and landfill/incineration activities would have to be included and would increase the impacts.

It is difficult to exactly quantify the data quality of this study. Globally the uncertainty is high, especially when secondary data also have their own uncertainty in the study they have been taken from. For example the inventory used to model crossing structures from the German railway study was developed on assumptions (Schmied and Mottschall, 2013). Crossing structures is probably the component with the highest uncertainty, any type of crossing structure (except viaduct) was assumed to have the same inventory while it would be closer to reality to have overpasses and bridges requiring a higher material intensity per metre than underpasses.

7.3.2.2 Rolling stock and its operational energy consumption

It may seem weird to not estimate an integer number of rail vehicles, but this just means that some vehicles will still be operational after the 60-year period. The number of rail vehicles was calculated based on assumptions regarding passenger and freight transport demand reported in the ESIA report (ERM, 2019, p. 418). The document they refer to does not seem to be publicly available online. Comparing the freight demand assumption (12.9 million tons/year by 2029) with the latest reported statistics by Ministry of works, transport, and communication (transport sector) (2017) reveals a rather large difference (total freight load, including the TAZARA line, in 2017 of 523,000 tons). The SGR-model is not a dynamic model and therefore does not consider the evolution of passenger and freight demand. A lower freight load would impact the number of rail vehicles, the total energy consumption for operations, and the maintenance activities.

Datasets from Ecoinvent were used to model the rolling stock, but without any information regarding the future rolling stock of the SGR, it is difficult to know if they model it properly especially in terms of kilometric lifetime, number of seats available, and material composition.

The energy consumption for operations considered in the SGR-model is also one element to discuss. In the ESIA report, there is no information regarding the way the specific energy consumptions per km have been calculated and if electricity losses in the railway power supply system are included. However, the energy consumption per passenger-kilometre and tonne-kilometre can be calculated to be compared with energy intensities in other countries.

With 1460 trains transporting 1.1 million passenger per year and an electricity consumption of 20.3 kWh/km, the electricity consumption per passenger-kilometre is:

$$Electricity\ consumption\ per\ pkm = \frac{20.3 * 541 * 1460}{1.1 * 10^6 * 541} = 0.027\ kWh/pkm = 97\ kJ/pkm$$

The same approach can be performed for freight. With 7040 trains per year and an electricity consumption of 76.6 kWh/km, the electricity consumption per tonne-kilometre is:

$$Electricity\ consumption\ per\ tkm = \frac{76.7 * 541 * 7040}{12.9 * 10^6 * 541} = 0.042\ kWh/tkm = 151\ kJ/tkm$$

Many parameters influence the energy intensity per passenger-kilometre and tonne-kilometre: energy consumption per vehicle-kilometre, occupancy, load, and electrification (IEA, 2019b). In 2016, the world energy intensity averages are about 120 kJ/pkm and 110 kJ/tkm but the energy intensities of passenger rail range between about 50 and 950 kJ/pkm and the energy intensities of freight rail range between about 40 and 340 kJ/tkm (IEA, 2019b, p. 54).

The energy intensities for passenger for the SGR is close to the world energy intensity of passenger rail and the energy intensity of freight rail for the SGR is above the world average, but comparable to European and North American energy intensities (IEA, 2019b). Therefore, the electricity consumptions for freight and passenger trains indicated in the ESIA reported were kept in the SGR-model, but some clarifications about how they were calculated and if losses at substations and in catenary are considered would be useful to provide more details about the underlying assumptions.

7.3.2.3 Background processes

In the SGR-model, Ecoinvent database v3.2 (Wernet *et al.*, 2016) was used to retrieve background processes data, but except for electricity, the database does not include specific processes for Tanzania. Tanzania does not have its own life cycle database, LCA research in the country is at an early stage, but development of LCA and country-specific database is encouraged (Felix, 2016).

7.3.2.4 Strenghts of this LCA study

Based on the different aspects developed in this section, one may notice that there is a lot of room for improvement. Nevertheless, the SGR-model and its LCA present some strengths worth mentioning.

Even if specific-project data collection did not succeed, an LCA model to estimate environmental impacts has been built. This LCA model lays the ground for further environmental research. It is possible to build upon this model using data specific for the SGR life cycles and expanding the system boundaries to improve the impact calculations and include some of the excluded activities.

The results have also identified some key elements to focus on such as use of steel and transport, and these elements could be the priority when collecting data to improve the model and when evaluating how to reduce the environmental impacts.

Since no specific-project data collection succeeded, alternative ways to collect data had to be found. Beyond the use of literature data, watching videos of the construction progress was performed to attempt to build a model slightly closer to what is built such as it has been done with the tunnels. This thesis therefore illustrates that online resources are also valuable while they could sometimes be considered as only having informative purposes.

8 Conclusions and further research

In this last chapter, conclusions based on the environmental impact results, scenario developments, and discussion are drawn. Ideas for further research built upon this thesis are also described.

8.1 Conclusions

The aim of this thesis has been to evaluate environmental impacts of a railway line in development in Africa. The Standard Gauge Railway in Tanzania was identified as a relevant case. A model, the SGR-model, was built to conduct a life cycle assessment, estimate environmental impacts, and develop some alternative scenarios.

Four main research questions were detailed in the introduction and provided guidelines to follow for this thesis. Answers to these questions are provided in the following paragraphs.

Main materials and energy requirements for the construction, maintenance, and operation of the SGR:

Based on the life cycle inventory, main materials required for the construction and maintenance of the SGR in Tanzania are gravel, concrete, and steel. Main energy requirements come from fuel consumption for machinery and transport. Regarding operation phase, electricity powering the SGR is mainly produced from natural gas, hydropower, and oil.

Contribution of the different life cycle stages to the environmental impacts:

The operation phase was found to have the highest contribution to climate change (75%), fossil depletion (82%), particulate matter formation (61%), and terrestrial acidification (74%). This results from the electricity supply mix composition. Natural gas and oil are fossil fuels and they have relatively high climate change, fossil depletion, particulate matter formation, and terrestrial acidification impacts in comparison with other sources of electricity production.

Regarding the infrastructure, construction and maintenance present a rather balanced contribution. However, maintenance only includes track maintenance activities which could lead to an underestimation of environmental impacts from the maintenance phase.

Contribution of the different railway infrastructure components and rail vehicles to the environmental impacts:

When analysing environmental impacts of the infrastructure, materials stood out as being the most contributing to freshwater eutrophication (97%), mineral resource depletion (95%), and human toxicity (99%). The use of steel and copper in the track and power and signalling system are the main contributors to these impacts. Transport of materials by lorry was also identified as a contributing activity.

Land use change (vegetation clearance) and concrete also contribute to climate change (11% and 9% respectively). Land transformation and gravel are the two largest contributors to natural land transformation.

Regarding the rolling stock, goods wagons generate most of its environmental impacts (more than 95% in all categories).

Scenarios influencing the environmental impacts:

Developing scenarios based on the LCA model of the SGR gave the opportunity to evaluate how environmental impacts of the railway line could be reduced and this reduction was quantified.

Producing a cleaner supply mix electricity appears to be the priority to improve the overall environmental performance of the SGR and especially reduce climate change, fossil depletion, particulate matter formation, and terrestrial acidification impacts (they can be reduced by 30%, 32%, 34% and 50% respectively in the renewables scenario). Lifetime extension of goods wagons and track components (rails, pads, and sleepers), and introduction of secondary steel during the maintenance phase present more limited effects but are worth considering especially in terms of mineral resource depletion, freshwater eutrophication, and human toxicity. Reducing transport distances has a very limited influence, but other aspects regarding transport could be explored such as fuel consumption efficiency and switching to rail transport of materials during the maintenance phase.

Based on the findings from the scenarios development, a combination of all the strategies investigated is suggested to improve the overall environmental performance of the SGR in Tanzania and enable a reduction, even if at various degree, of all impact categories.

Trade-offs between climate change mitigation and other environmental impact categories:

While mitigating climate change impact, electricity scenarios presented increases in other environmental categories (freshwater eutrophication, human toxicity, and mineral resource depletion). However, these increases have been discussed based on the contribution of the respective impact categories to the endpoint indicators from ReCiPe. This discussion indicates that the decrease in climate change impact outbalances the increase in freshwater eutrophication, human toxicity, and mineral resource depletion and still leads to a reduction of the indicators' values.

8.2 Further research

Several directions can be explored as future work based on this thesis. In this section, some of them are described.

Environmental impacts of the SGR in Tanzania have been estimated by collecting data from various sources to build the SGR-model and conduct a life cycle assessment. To improve the results, it is recommended to get project-specific data for both the railway components (such as length of bridges) or the inputs to build each component (materials, transport, energy use).

Some scenarios have been developed to evaluate the potential reduction of environmental impacts. However, introducing secondary materials or extending component lifetime is not as easy as simply doing the impact calculations. Further research is necessary to know how materials can be replaced and in which quantities to respect technical and safety constraints. This research could also be conducted through discussions with railway experts.

Only electricity consumption to power the rail vehicles was included. It is suggested to also include the energy consumption for infrastructure such as electricity use by passenger stations. It has been shown that the operation phase has globally the highest environmental impacts due to the heavy presence of fossil fuels in the composition of the electricity supply mix. Electricity supply mix scenarios were implemented, but additional scenarios could also be explored and discuss more specifically how to expand the use of renewables and maybe directly power the railway line. Moreover, the scenario-based framework developed in this thesis was built upon a static analysis while changes in electricity production mix would be a continuous process. Introducing a dynamic perspective to evaluate this continuous change would allow a better understanding of environmental impact improvement of the operation phase.

One of the purposes for building the SGR in Tanzania is to reduce overloading of roads. Studying transfer from roads to rail as well as estimating the payback period would provide a larger overview of the environmental aspects related to the SGR. However, studying a transfer from road to rail would probably require including dynamic changes in terms of passenger and freight transport.

As the results indicate, land use change contributes to climate change and natural land transformation impacts. About 11% of climate change and 97% of natural land transformation from infrastructure were estimated to result from land transformation and clearing the Right-of-Way of its vegetation. Land occupation was estimated but was not selected among the impact categories to analyse in this thesis, but the impact should be investigated. Moreover, railway lines impact natural habitats and wildlife. These impacts are discussed in the ESIA report (ERM, 2019). Likewise, Borda-de-Água *et al.* (2017) highlight the importance of considering how biodiversity is affected by railway lines. However, since this was not part of this thesis, it is recommended to explore impacts from the construction and operation of railway lines on biodiversity in the regions crossed by the SGR and think how life cycle assessment methodology could include such impacts.

Finally, beyond the investigation of environmental impacts of the SGR under construction in Tanzania, this thesis is to encourage future research about railway development and environmental impacts assessment in Africa. Building and using LCA models to investigate potential environmental impacts of railway development in the East African region and Africa could guide decision makers in implementing new railway lines and choosing among several railway corridors to build.

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Appendices

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Appendix A – Density of materials

Process	Density (kg/m^3)	Comment	Source
Soil	1380	This value represents the bulk density for topsoil layer (0-30cm), but in the SGR-model this value is assumed to be representative of the density of excavated soil during construction and is used to estimate transport activity in tonne-kilometre.	(Kempen *et al.*, 2019)
Concrete, normal	2370	-	(Werner, no date b)
Concrete, 25MPa	2409	-	(Martineau, no date a)
Concrete, 35MPa	2315	-	(Martineau, no date b)
Concrete, high exacting requirements	2420	-	(Werner, no date a)
PVC-P	1350	Density considered for the membrane in tunnel construction.	(Stuart, 2005, p. 53)
Steel	7850	-	(Classen *et al.*, 2009)
Ballast	1620	-	(Stripple and Uppenberg, 2010)
Crushed rock (excavated material from tunnel construction)	1600	For transport of excavated masses from tunnelling activities.	(von Rozycki, Koeser and Schwarz, 2003)

Diesel: 1 L is 36 MJ (energy density calculated based on density of diesel is 0.84 kg/L and diesel net calorific value is 42.8 MJ/kg) (Weidema et al., 2013).

Appendix B – Supplementary material regarding life cycle inventory

B1 - Vegetation and land clearance

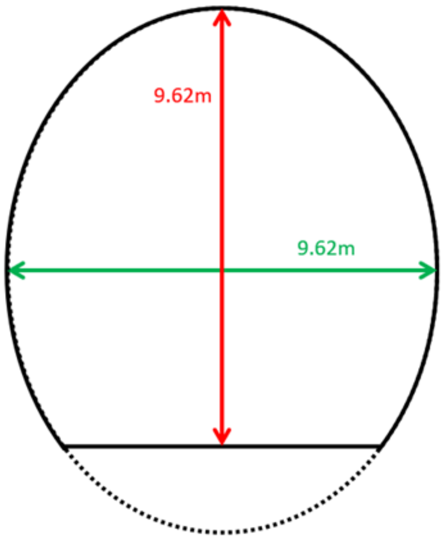
Land cover	**Lot 1**				**Lot 2**				**Land cover type associated for the most important land covers**	**Carbon stock**	**CO_2 emissions**	
	RoW		**Facilities***		**RoW**		**Facilities***					
	Hectares (Ha)	**% of total area**	**Hectares (Ha)**	**% of total area**	**Hectares (Ha)**	**% of total area**	**Hectares (Ha)**	**% of total area**		**tC/Ha**	**tCO_2 /Ha**	**Lot1 + Lot2 (tCO_2)**
Bare land	0	0%	0.12	0%	2	0%	0	0%	-	-	-	-
Built up areas	61	4%	0	0%	20	1%	0.01	0%	-	-	-	-
Cropland	435	29%	126	16%	857	39%	138	37%	Cultivated land: grain and herbaceous crops (50:50)	3.45	12.65	19683
Grassland	626	42%	362	46%	258	12%	58	16%	Wooded grassland	7.2	26.40	34426
Lichen mosses/sparse vegetation	0	0%	0	0%	0.08	0%	0.09	0%	-	-	-	-
Open water	0	0%	0	0%	0	0%	0	0%	-	-	-	-
Shrubs cover areas	116	8%	49	6%	896	41%	122	33%	Bushland: open	14.3	52.43	62029
Trees cover areas	258	17%	246	31%	156	7%	53	14%	Overall for forest	33.4	122.28	87188
Vegetation aquatic or regularly flooded	2	0%	0	0%	0.39	0%	0.2	0%	-	-	-	-
TOTAL	1498	100%	783.12	100%	2189.47	100%	371.3	100%				203326
*(Borrow pits, dumping sites, quarry sites, construction of marshalling yards, stations and campsites) Source: (ERM, 2019, pp. 290–292) (Tables 4-38, 4-39, 4-40, 4-41)									Source: (Mauya *et al.*, 2019)			

B2 – Comparison of earthworks with other railway lines in Africa

Railway line	Main line length (m)	Earthworks (m3)	Earthworks (m3/m main line)
SGR - Kenya - Scheme 1[a]	485,303	7,49E+07	154
SGR - Kenya - Scheme 2[a]	493,000	4,63E+07	94
SGR - Kenya - Scheme 3[a]	471,500	6,91E+07	146
AkH – Ethiopia[b]	392,000	9,77E+07	249
AkH – Ethiopia[c]	390,000	9,90E+07	254
Djibouti - Addis Ababa[d]	751,700	4,01E+07	53
Sources: [a] (Africa Waste and Environment Management Centre, 2012, p. 145), [b](AKH Railway Project, no date) , [c](Yapı Merkezi, 2018a), [d](CR2, 2018)			

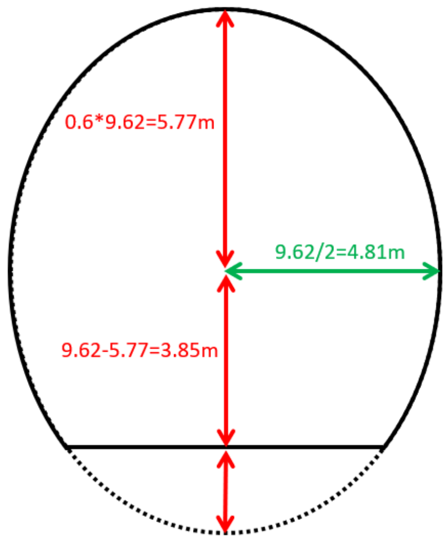
B3 - Tunnel cross-section dimensions

In a video (TRC RELI TV, 2019) showing the construction of one of the tunnels of the SGR, it is possible to see at 2min43 and 3min23 that some values are written on the concrete wall at the entrance of the tunnel. Specifically, the value "9.62" which seems to correspond to the top of the tunnel. In this project, it is assumed that the height of the tunnel is then 9.62 m. Based on a screenshot of the video at 3min23, an ellipse form is sketched and represented in the following figure. Since the minor axis of the ellipse seems to have the same length as the tunnel height, the same value "9.62" is selected.



Tunnel profile (video (TRC RELI TV, 2019) *at 3min23)*

The semi-major axis values can be determined based on proportional relationships.



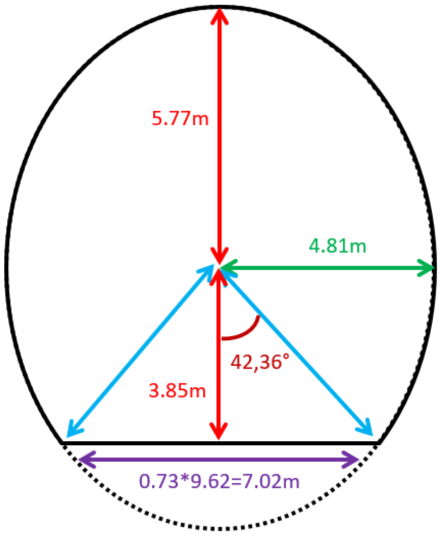
Tunnel profile – Calculations of dimensions

From the figure above can be calculated the total elliptical area and perimeter:

$$Total\ elliptical\ area = \pi * 4.81 * 5.77 = 87.19m^2$$

$$Total\ elliptical\ perimeter\ (approximation) \approx 2 * \pi * \sqrt{\frac{4.81^2 + 5.77^2}{2}} = 33.37m$$

Additional calculations lead to the following measures on the figure.

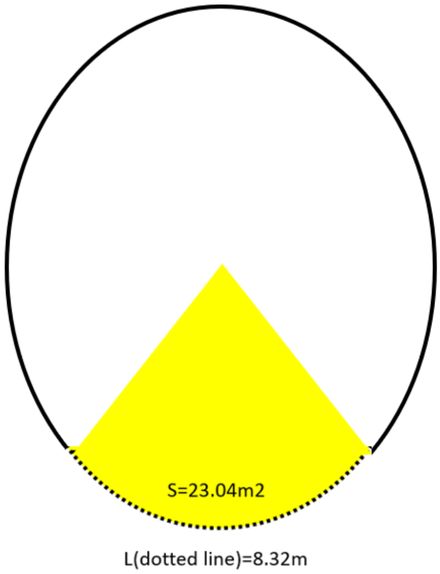


Tunnel profile – Calculations of dimensions

The blue and purple lengths are determined based on proportional relationships while the angular value is calculated with a trigonometric formula:

$$Angle = \tan^{-1}\left(\frac{\frac{7.02}{2}}{3.85}\right) = 42.36°$$

An online calculator (https://keisan.casio.com/exec/system/1343722259) is used to estimate the area and arc length of the elliptical sector comprised between the dotted line and the blue arrow. The following figure represents the results and the elliptical sector in yellow.

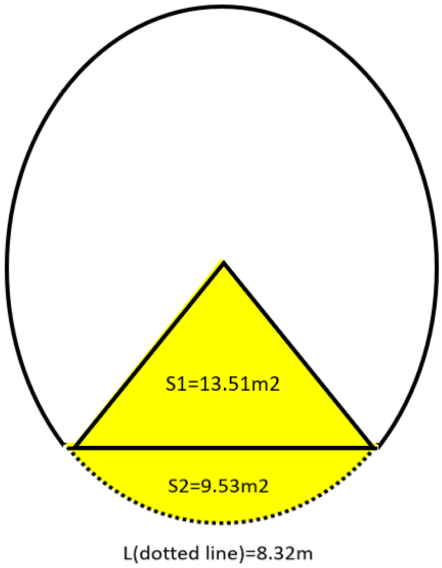


Tunnel profile – Elliptical sector area and arc length

Only the elliptical lower part needs to be considered, then the area of the triangle is removed:

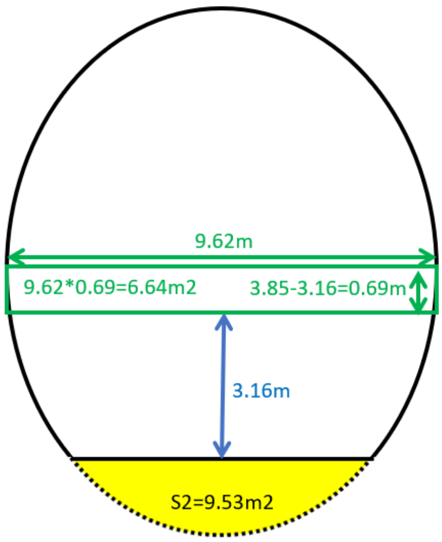
$$S1 = \frac{3.85 * 7.02}{2} = 13.51m^2$$

$$S2 = S - S1 = 23.04 - 13.51 = 9.53m^2$$



Tunnel profile – Elliptical lower part dimensions

Based on observations in the video, it seems that the tunnel is excavated in two parts: explosives are used for the upper part of the tunnel while a breaker machine is used for the lower part. The height "3.16" of the lower part is shown at 2min43 in the same video (TRC RELI TV, 2019).



Tunnel profile – Lower part excavation dimensions

To estimate the amount of excavated rocks in the lower part, the green part is assumed to be a rectangle and the following calculation is done:

$$Lower\ part\ excavated\ area = \frac{87.2}{2} - 9.53 - 6.64 = 27.8m2$$

Therefore, the tunnel profile is described in the following table:

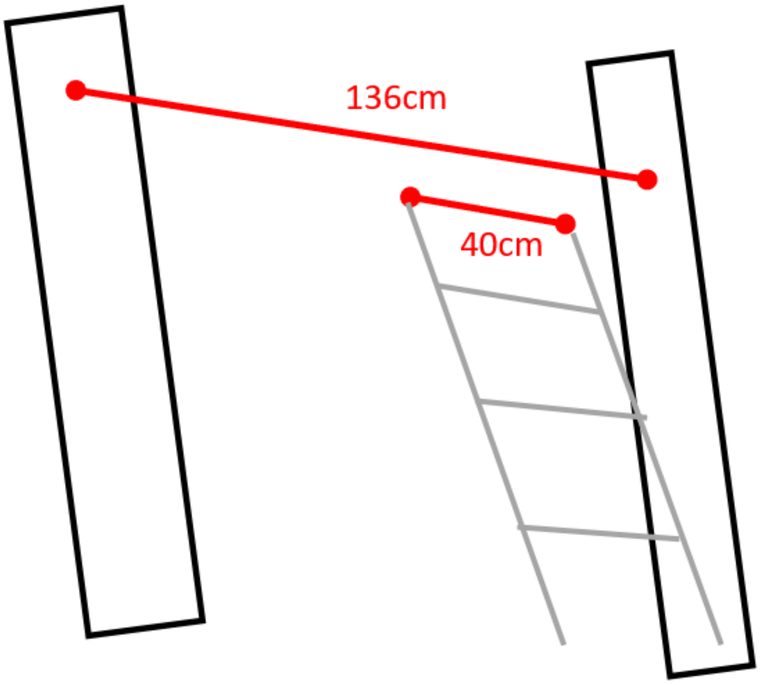
Tunnel excavated profile dimensions

Excavated profile (total)	$87.19 - 9.53 = 77.66m^2 \rightarrow 78m^2$
Excavated profile (lower part using machinery)	$27.8m^2$
Excavated profile (upper part using explosives)	$78 - 27.8 = 50.2m^2$
Tunnel arc length	$33.37 - 8.32 = 25.05m \rightarrow 25m$

B4 – Distances between arches in the tunnel

In a video (TRC RELI TV, 2019) showing the construction of one of the tunnels of the SGR, it is possible to see at 4min58, a worker on a ladder against the wall of the tunnel between two steel arches. Based on the screenshot, a sketch representing the ladder and the two steel arches has been done.

It is assumed that the ladder is about 40 cm wide which allows to estimate the distance center/center between two arches.



Distance between two arches in steel

It is therefore considered a distance of 140cm between two steel arches.

B5 – Average culvert length

Railway	Culverts (nb)	Culverts (m)	Culvert length (m/culvert)	Average culvert length (m/culvert)
SGR – Kenya[a]	969	27,746	28.63	33.75
AkH – Ethiopia[b]	884	34,500	39.03	
AkH – Ethiopia[c]	900	43,000	47.78	
Djibouti - Addis Ababa[d]	453	8,855	19.55	
Sources: [a](Africa Waste and Environment Management Centre, 2012), [b](AKH Railway Project, no date) , [c](Yapı Merkezi, 2018a), [d](CR2, 2018)				

B6 – Transport of materials

B6.1. Earthworks material

The average distance to reach a dumping site has been estimated as 6.3 km based on the dumping site locations[14] (ERM, 2019, pp. 66–67). However, as some excavated material is used as fill material, it is assumed that it is on average transported over 10 km by truck either to be dumped in dumping sites, either to be used as fill material.

B6.2. Track materials

In this section, average distances for the different track components are calculated.

Ballast
The ESIA report mentions that ballast is locally produced from quarry sites and aggregate crushing facilities located at Lugoba (ERM, 2019, p. 46). By assuming this is the only location producing ballast for the whole track, the average distance for ballast transport from Lugoba is calculated.

No GPS coordinates, nor exact transport route are available. Therefore, Google Maps distances are used: Lugoba is approximately located at 388 km from Makutupora and 121 km from Dar Es Salaam. Thus, about 76% of the ballast produced at Lugoba goes in the direction of Makutupora, transported over an average distance of 194 km and 24% goes in the direction of Dar Es Salaam, transported over an average distance of 61 km. This results in an average distance of:

$$ballast\ transport\ (average\ distance) = 0.76 * 194 + 0.24 * 61 = 162\ km$$

Sleepers
Sleepers are produced in sleeper factories located along the tracks. The locations of two sleeper factories are retrieved from videos of the construction progress: a first factory is located at kilometre 55+000 – shown at 5min27 (Yapı Merkezi Tanzania, 2018) and a second factory is located at kilometre 395+000 – shown at 9min38 (Yapı Merkezi Tanzania, 2020d). It is assumed that these two factories are the only factories along the SGR and that sleepers are distributed by truck from one factory until the start (for factory 1)/end (for factory 2) of the railway line and middle point between the two factories. Thus, about 42% of the sleepers are produced by the factory 1 and about 58% of the sleepers are produced by the factory 2.

For factory 1, about 24% of the sleepers are distributed over an average distance of 27.5 km and 76%, over an average distance of 85km. The average transport distance of sleepers from factory 1 is estimated:

$$sleeper\ transport\ (average\ distance\ from\ factory\ 1) = 0.24 * 27.5 + 0.76 * 85 = 71\ km$$

For factory 2, about 54% of the sleepers are distributed over an average distance of 85 km and 46%, over an average distance of 74 km. The average transport distance of sleepers from factory 2 is estimated:

$$sleeper\ transport\ (average\ distance\ from\ factory\ 1) = 0.54 * 85 + 0.46 * 74 = 79\ km$$

Therefore, for all the sleepers, the average transport distance is:

[14] Calculation of average distance between [distance between start of line and first dumping site, average distance two dumping sites, distance last dumping site and end of line]

$$sleeper\ transport\ (average\ distance) = 0{,}42 * 71 + 0{,}58 * 79 = 76\ km$$

Regarding the materials used for the manufacturing of sleepers, it is assumed that concrete is produced on site at the sleeper factories and that steel is imported (refer to transportation of metals products).

Rails

According to an article (published on the 2nd of September 2018) from on online newspaper, rails seem to be imported from Japan (The Guardian Reporter, 2018). To estimate the transport distance, a shipping distance (between Tokyo and Dar Es Salaam) of 13,000 km is considered and has been estimated by using a digital tool (SeaRates LLC, 2020). Then, rails are transported from the port of Dar Es Salaam to the construction site. Is it assumed that rails are directly transported from the port to the location where they are placed on the tracks. Since the track route is 541 km, an average distance of 270.5 km by truck is considered. Is is further assumed that any product arriving at the port of Dar Es Salaam is transport by truck over an average distance of 270.5 km.

Fastenings & pads

It is assumed that fastenings and pads have the transport pattern as the rails.

B6.3. Power and signalling system

Two main material categories are used in the construction of the power supply and signalling system in the SGR-model: concrete and metals.

Regarding the transport of concrete: it is assumed to be produced locally (there are several batching plants, nine in total, along the SGR (ERM, 2019, p. 55)). For some of them, the location is mentioned in the ESIA report, but the location is not known for the others. Since there are nine batching plants, concrete is assumed to be transported by truck over an average distance of 30 km.

Regarding the transport of metals: according to the World Integrated Trade Solution by the World Bank, in 2018, Tanzania imported its metals mainly from China, South Africa, India and Japan (World Bank, 2020). To estimate an average shipping transport distance for metals: the import value in US dollars and the shipping distances in km by using a digital tool (SeaRates LLC, 2020) have been considered to calculate a weighted average distance based on import values. This results in an average transport value of 9000 km. Then, metals products are transported by truck along the SGR over a transport distance of 270.5 km.

B6.4. Tunnels

The first activity in tunnel construction is the excavation of rocks. The same transport assumption as for earthwork material is assumed for excavated rocks: an average transport distance over 10 km by truck.

For some materials required for the construction of the tunnels (explosives, PVC), market processes from Ecoinvent database v3.2 (Wernet *et al.*, 2016) have been considered. These processes already include average transport activities.

Regarding concrete, it is assumed to be transported by truck over the same average distance as for the Power supply and signalling system, meaning 30 km. It is also assumed that cement has the same transport.

For steel elements, the same shipping distance as for metals in power supply and signalling system is assumed (9000 km) but an average distance of 282 km by truck is assumed from the port of Dar Es Salaam since the four tunnels are located kilometre point 271+136 (entrance tunnel 1) and kilometre point 292+193 (exit tunnel 4) (Yapı Merkezi Tanzania, 2020d).

B6.5. Crossing structures and culverts

As for tunnels, excavated materials resulting from crossing structures construction are assumed to be transported over 10 km.

Concrete and steel required for the construction of crossing structures and culverts are assumed to have the same transport as for the power and signalling system, respectively 30 km by truck, and 9000 km by ship and 270.5 km by truck.

B7 – Material and energy requirements of the SGR-model

Construction	Land use change	Earthworks	Track	PSS	Tunnel	Crossing structures	Viaduct	Culverts	Total
Length (m)	**541000**	**541000**	**722000**	**722000**	**2620**	**7937**	**2560**	**32397**	
Steel (low-alloyed) (kg)	0.00E+00	0.00E+00	1.01E+08	1.93E+07	0.00E+00	1.07E+06	8.06E+05	0.00E+00	1.23E+08
Reinforcing steel (kg)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.55E+06	6.07E+06	4.57E+06	7.40E+06	2.46E+07
Concrete (kg)	0.00E+00	0.00E+00	3.25E+08	8.17E+07	1.41E+08	1.61E+08	1.19E+08	1.67E+08	9.95E+08
Cement (kg)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.25E+06	0.00E+00	0.00E+00	0.00E+00	5.25E+06
Gravel (kg)	0.00E+00	0.00E+00	2.92E+09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.92E+09
Explosives (kg)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.24E+05	0.00E+00	0.00E+00	0.00E+00	2.24E+05
Plastics (kg)	0.00E+00	0.00E+00	9.63E+05	0.00E+00	1.77E+05	0.00E+00	0.00E+00	0.00E+00	1.14E+06
Copper (kg)	0.00E+00	0.00E+00	0.00E+00	1.97E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.97E+06
Bronze (kg)	0.00E+00	0.00E+00	0.00E+00	1.11E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.11E+06
Aluminium (kg)	0.00E+00	0.00E+00	0.00E+00	1.05E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.05E+06
Processing metals (kg)	0.00E+00	0.00E+00	1.01E+08	2.24E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+08
Vegetation clearance (kgCO2)	2.03E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.03E+08
Land transformation (m2)	3.69E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.69E+07
Electricity (kWh)	0.00E+00	0.00E+00	3.89E+06	0.00E+00	7.86E+06	0.00E+00	0.00E+00	0.00E+00	1.17E+07
Diesel & Machinery (MJ)	0.00E+00	0.00E+00	2.22E+07	2.95E+07	5.09E+06	0.00E+00	0.00E+00	0.00E+00	5.68E+07
Excavation (m3)	0.00E+00	7.82E+07	0.00E+00	0.00E+00	7.28E+04	2.48E+04	3.99E+04	0.00E+00	7.83E+07
Transport - Import (tkm)	0.00E+00	0.00E+00	1.28E+09	2.11E+08	5.89E+07	6.43E+07	4.84E+07	6.66E+07	1.73E+09
Transport - Lorry (tkm)	0.00E+00	5.40E+08	5.27E+08	8.78E+06	9.50E+06	7.11E+06	5.57E+06	7.01E+06	1.10E+09

Table below represents material and energy requirements for each maintenance activity. The requirements need to be multiplied with the number of times each activity is performed over 60 years to estimate the total material and energy requirements apart from land use change which a process occurring over the 60 years.

Maintenance	Land use change	Rail renewal	Sleepers renewal	Fastenings renewal	Pads renewal	Ballast tamping	Ballast cleaning	Ballast renewal
Length (m)	**541000**	**722000**	**722000**	**722000**	**722000**	**722000**	**722000**	**722000**
Steel (low-alloyed) (kg)	0.00E+00	8.69E+07	1.16E+07	2.89E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Concrete (kg)	0.00E+00	0.00E+00	3.25E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gravel (kg)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.46E+08	8.77E+08	2.92E+09
Plastics (kg)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.63E+05	0.00E+00	0.00E+00	0.00E+00
Processing metals (kg)	0.00E+00	8.69E+07	1.16E+07	2.89E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Electricity (kWh)	0.00E+00	0.00E+00	3.89E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Diesel & Machinery (MJ)	0.00E+00	4.81E+06	1.82E+06	0.00E+00	0.00E+00	1.25E+07	1.91E+07	1.91E+07
Transport - Import (tkm)	0.00E+00	1.13E+09	1.04E+08	3.75E+07	1.25E+07	0.00E+00	0.00E+00	0.00E+00
Transport - Lorry (tkm)	0.00E+00	2.35E+07	2.87E+07	7.81E+05	2.60E+05	2.37E+07	1.42E+08	4.74E+08
Land occupation (m2a)	2.21E+09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table below represents material and energy requirements for each end-of-life activity. The requirements need to be multiplied with the number of times each activity is performed over 60 years to estimate the total material and energy requirements.

EoL	Rails dismantling	Sleepers dismantling	Pads disposal
Length (m)	**722000**	**722000**	**722000**
Diesel & Machinery (MJ)	4.81E+06	1.82E+06	0.00E+00
Transport (tkm)	0.00E+00	0.00E+00	1.93E+05
Landfill (kg)	0.00E+00	0.00E+00	-9.63E+05

Appendix C – Supplementary material regarding life cycle impact assessment

C1 - Disaggregation of environmental impacts from materials, energy, and transport

Impact category	Materials										
	Steel (LA)	Rebar	Concrete	Cement	Gravel	Expl.	Plastics	Copper	Bronze	Alu.	Pro. metals
Climate change (kg CO2 eq)	6.36E+08	5.31E+07	1.61E+08	4.75E+06	1.45E+08	1.26E+06	7.39E+06	1.04E+07	5.20E+06	1.85E+07	8.47E+07
Fossil depletion (kg oil eq)	1.48E+08	1.31E+07	1.90E+07	4.08E+05	3.66E+07	2.07E+05	4.57E+06	2.40E+06	1.23E+06	3.79E+06	2.41E+07
Freshwater eutrophication (kg P eq)	6.87E+05	3.21E+04	2.00E+04	4.52E+02	6.86E+04	2.54E+02	1.96E+03	2.88E+05	7.45E+04	6.55E+03	4.12E+04
Human toxicity (kg 1,4-DB eq)	8.94E+08	3.12E+07	2.01E+07	3.80E+05	5.94E+07	3.21E+05	2.83E+06	6.85E+08	1.61E+08	5.60E+06	4.50E+07
Mineral resource depletion (kg Fe eq)	1.35E+09	4.90E+07	3.15E+06	3.14E+04	1.44E+07	5.97E+04	3.00E+05	9.48E+07	3.01E+07	1.87E+06	2.15E+07
Natural land transformation (m2)	6.44E+04	5.97E+03	2.17E+04	2.53E+02	2.08E+05	1.42E+02	2.60E+03	3.80E+03	2.64E+03	1.68E+03	1.30E+04
Particulate matter formation (kg PM10 eq)	2.98E+06	2.08E+05	1.92E+05	4.34E+03	4.77E+05	2.31E+03	1.46E+04	2.91E+05	1.09E+05	5.45E+04	2.49E+05
Terrestrial acidification (kg SO2 eq)	2.81E+06	2.16E+05	3.96E+05	9.19E+03	7.82E+05	5.85E+03	3.08E+04	9.42E+05	3.19E+05	1.00E+05	3.57E+05

Steel (LA) = Steel (low-alloyed), Rebar = Reinforcing steel, Expl. = Explosives, Alu. = Aluminium, Pro. metals = Processing metals

Impact category	Energy			Transport	
	El.	Diesel & Machin.	Excav.	Import	Lorry
Climate change (kg CO2 eq)	1.16E+07	3.37E+07	4.23E+07	4.01E+07	3.87E+08
Fossil depletion (kg oil eq)	4.02E+06	1.18E+07	1.46E+07	1.32E+07	1.41E+08
Freshwater eutrophication (kg P eq)	2.64E+02	1.57E+03	2.96E+03	5.48E+03	3.34E+04
Human toxicity (kg 1,4-DB eq)	8.13E+05	1.86E+06	3.33E+06	4.76E+06	8.46E+07
Mineral resource depletion (kg Fe eq)	1.04E+05	1.29E+06	2.90E+06	1.05E+06	1.37E+07
Natural land transformation (m2)	2.96E+03	1.15E+04	1.39E+04	1.30E+04	1.39E+05
Particulate matter formation (kg PM10 eq)	1.58E+04	1.40E+05	1.74E+05	2.56E+05	9.45E+05
Terrestrial acidification (kg SO2 eq)	5.71E+04	2.71E+05	3.33E+05	7.83E+05	1.71E+06

El. = Electricity, Diesel & Machin. = Diesel & Machinery, Excav. = Excavation

C2 – Environmental impact results for each railway component included in the SGR-model infrastructure

Earthworks

Impact category	Excavation	Transport - Lorry	TOTAL
Climate change (kg CO2 eq)	4.23E+07	7.17E+07	1.14E+08
Fossil depletion (kg oil eq)	1.46E+07	2.62E+07	4.08E+07
Freshwater eutrophication (kg P eq)	2.96E+03	6.20E+03	9.15E+03
Human toxicity (kg 1,4-DB eq)	3.32E+06	1.57E+07	1.90E+07
Mineral resource depletion (kg Fe eq)	2.90E+06	2.54E+06	5.44E+06
Natural land transformation (m2)	1.39E+04	2.57E+04	3.96E+04
Particulate matter formation (kg PM10 eq)	1.73E+05	1.75E+05	3.49E+05
Terrestrial acidification (kg SO2 eq)	3.32E+05	3.17E+05	6.49E+05

Track

Impact category	Ballast	Rails	Sleepers	Fastenings	Pads	Diesel & Machinery	Transport	Total
Climate change (kg CO2 eq)	1.45E+08	5.67E+08	1.72E+08	1.80E+07	7.04E+06	3.05E+07	3.45E+08	1.28E+09
Fossil depletion (kg oil eq)	3.66E+07	1.36E+08	3.02E+07	4.49E+06	4.38E+06	1.06E+07	1.25E+08	3.47E+08
Freshwater eutrophication (kg P eq)	6.86E+04	5.69E+05	8.80E+04	1.60E+04	1.94E+03	1.42E+03	3.16E+04	7.76E+05
Human toxicity (kg 1,4-DB eq)	5.94E+07	7.28E+08	1.10E+08	2.07E+07	2.81E+06	1.68E+06	7.20E+07	9.94E+08
Mineral resource depletion (kg Fe eq)	1.44E+07	1.08E+09	1.46E+08	2.74E+07	2.98E+05	1.17E+06	1.19E+07	1.28E+09
Natural land transformation (m2)	2.08E+05	5.86E+04	2.40E+04	1.99E+03	2.59E+03	1.04E+04	1.22E+05	4.28E+05
Particulate matter formation (kg PM10 eq)	4.77E+05	2.54E+06	4.53E+05	7.59E+04	1.42E+04	1.26E+05	9.80E+05	4.67E+06
Terrestrial acidification (kg SO2 eq)	7.82E+05	2.47E+06	5.79E+05	7.86E+04	2.98E+04	2.45E+05	2.05E+06	6.24E+06

Power & Signalling system

Impact category	Steel (low-alloyed)	Copper	Bronze	Aluminium	Processing metals	Concrete	Diesel & Machinery	Transport	Total
Climate change (kg CO2 eq)	4.64E+07	1.04E+07	5.20E+06	1.85E+07	7.85E+06	9.03E+06	2.72E+06	3.54E+06	1.04E+08
Fossil depletion (kg oil eq)	1.08E+07	2.40E+06	1.23E+06	3.79E+06	2.29E+06	1.08E+06	9.50E+05	1.21E+06	2.38E+07
Freshwater eutrophication (kg P eq)	5.03E+04	2.88E+05	7.45E+04	6.55E+03	1.12E+04	1.16E+03	1.26E+02	4.26E+02	4.32E+05
Human toxicity (kg 1,4-DB eq)	6.54E+07	6.85E+08	1.61E+08	5.60E+06	2.04E+07	1.15E+06	1.50E+05	5.38E+05	9.39E+08
Mineral resource depletion (kg Fe eq)	9.87E+07	9.48E+07	3.01E+07	1.87E+06	4.76E+06	1.79E+05	1.04E+05	1.03E+05	2.31E+08
Natural land transformation (m2)	4.70E+03	3.80E+03	2.64E+03	1.68E+03	1.10E+03	1.24E+03	9.26E+02	1.19E+03	1.73E+04
Particulate matter formation (kg PM10 eq)	2.18E+05	2.91E+05	1.09E+05	5.45E+04	3.22E+04	1.07E+04	1.13E+04	1.80E+04	7.45E+05
Terrestrial acidification (kg SO2 eq)	2.05E+05	9.42E+05	3.19E+05	1.00E+05	6.53E+04	2.20E+04	2.19E+04	5.16E+04	1.73E+06

Tunnels

Impact category	Reinforcing steel	Concrete	Cement	Explosives	Plastics	Electricity	Diesel & Mach. + Excav.	Transport	Total
Climate change (kg CO2 eq)	1.41E+07	1.19E+07	4.75E+06	1.26E+06	3.51E+05	5.33E+06	5.10E+05	1.93E+06	4.02E+07
Fossil depletion (kg oil eq)	3.48E+06	1.51E+06	4.08E+05	2.07E+05	1.87E+05	1.84E+06	1.78E+05	6.79E+05	8.48E+06
Freshwater eutrophication (kg P eq)	8.54E+03	1.60E+03	4.52E+02	2.54E+02	1.12E+01	1.20E+02	2.46E+01	2.00E+02	1.12E+04
Human toxicity (kg 1,4-DB eq)	8.30E+06	1.66E+06	3.80E+05	3.21E+05	2.30E+04	3.72E+05	2.90E+04	3.55E+05	1.14E+07
Mineral resource depletion (kg Fe eq)	1.30E+07	2.80E+05	3.14E+04	5.97E+04	1.25E+03	4.76E+04	2.07E+04	6.21E+04	1.35E+07
Natural land transformation (m2)	1.59E+03	1.92E+03	2.53E+02	1.42E+02	4.49E+00	1.35E+03	1.73E+02	6.67E+02	6.10E+03
Particulate matter formation (kg PM10 eq)	5.54E+04	1.53E+04	4.34E+03	2.31E+03	3.41E+02	7.21E+03	2.11E+03	7.32E+03	9.44E+04
Terrestrial acidification (kg SO2 eq)	5.75E+04	3.12E+04	9.19E+03	5.85E+03	9.29E+02	2.61E+04	4.09E+03	1.86E+04	1.53E+05

Crossing structures & Viaduct

Impact category	Steel (low-alloyed)	Reinforcing steel	Concrete	Excavation	Transport	Total
Climate change (kg CO2 eq)	4.52E+06	2.30E+07	3.20E+07	3.50E+04	2.96E+06	6.25E+07
Fossil depletion (kg oil eq)	1.05E+06	5.65E+06	3.75E+06	1.21E+04	1.03E+06	1.15E+07
Freshwater eutrophication (kg P eq)	4.90E+03	1.39E+04	3.94E+03	2.45E+00	3.20E+02	2.30E+04
Human toxicity (kg 1,4-DB eq)	6.37E+06	1.35E+07	3.95E+06	2.75E+03	5.20E+05	2.43E+07
Mineral resource depletion (kg Fe eq)	9.61E+06	2.12E+07	6.13E+05	2.40E+03	9.29E+04	3.15E+07
Natural land transformation (m2)	4.57E+02	2.58E+03	4.24E+03	1.15E+01	1.01E+03	8.30E+03
Particulate matter formation (kg PM10 eq)	2.12E+04	9.01E+04	3.79E+04	1.44E+02	1.22E+04	1.62E+05
Terrestrial acidification (kg SO2 eq)	2.00E+04	9.35E+04	7.82E+04	2.75E+02	3.23E+04	2.24E+05

Culverts

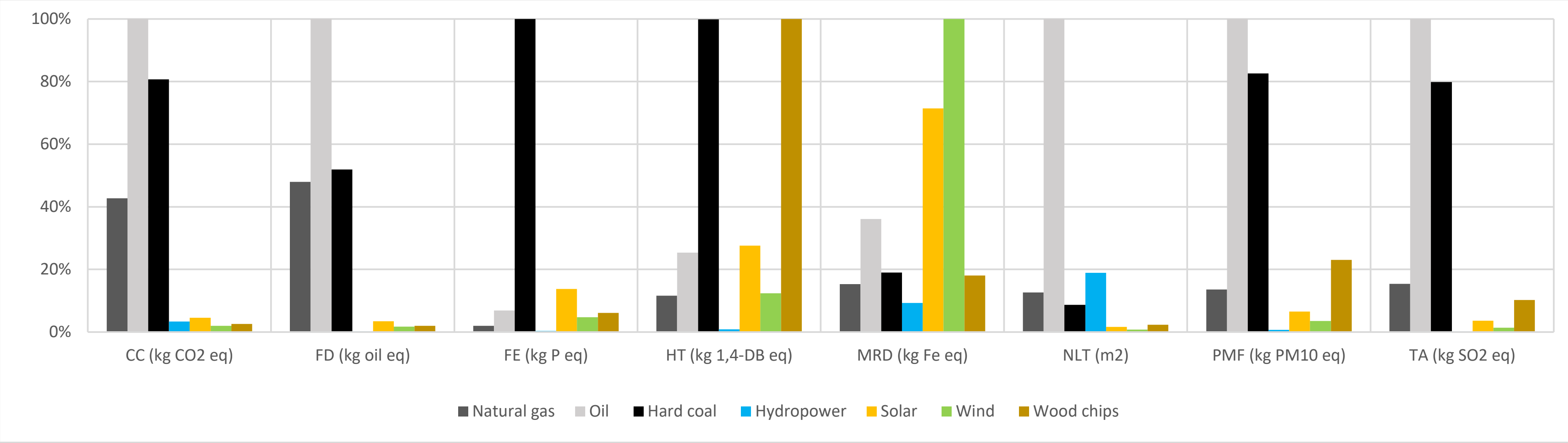
Impact category	Reinforcing steel	Concrete	Transport	Total
Climate change (kg CO2 eq)	1.60E+07	1.91E+07	1.68E+06	3.68E+07
Fossil depletion (kg oil eq)	3.93E+06	2.24E+06	5.87E+05	6.75E+06
Freshwater eutrophication (kg P eq)	9.65E+03	2.35E+03	1.83E+02	1.22E+04
Human toxicity (kg 1,4-DB eq)	9.37E+06	2.35E+06	2.93E+05	1.20E+07
Mineral resource depletion (kg Fe eq)	1.47E+07	3.65E+05	5.26E+04	1.52E+07
Natural land transformation (m2)	1.80E+03	2.52E+03	5.77E+02	4.90E+03
Particulate matter formation (kg PM10 eq)	6.26E+04	2.26E+04	7.06E+03	9.23E+04
Terrestrial acidification (kg SO2 eq)	6.50E+04	4.66E+04	1.88E+04	1.30E+05

C3 - Environmental impacts of the SGR-model infrastructure broken down into open section, tunnel section, and crossing structure section

Impact category	Total impact per section			Impact per section metre		
	Open section	Tunnel section	Crossing structure section	Open section	Tunnel section	Crossing structure section
Climate change (kg CO2 eq)	1.73E+09	4.62E+07	7.36E+07	3.26E+03	1.76E+04	8.58E+03
Fossil depletion (kg oil eq)	4.14E+08	9.83E+06	1.43E+07	7.82E+02	3.75E+03	1.67E+03
Freshwater eutrophication (kg P eq)	1.21E+06	1.56E+04	3.42E+04	2.29E+00	5.95E+00	3.99E+00
Human toxicity (kg 1,4-DB eq)	1.94E+09	1.84E+07	4.39E+07	3.66E+03	7.04E+03	5.12E+03
Mineral resource depletion (kg Fe eq)	1.52E+09	1.90E+07	4.52E+07	2.86E+03	7.27E+03	5.26E+03
Natural land transformation (m2)	1.49E+07	7.92E+04	2.46E+05	2.82E+01	3.02E+01	2.87E+01
Particulate matter formation (kg PM10 eq)	5.80E+06	1.14E+05	2.04E+05	1.09E+01	4.35E+01	2.37E+01
Terrestrial acidification (kg SO2 eq)	8.65E+06	1.82E+05	2.88E+05	1.63E+01	6.96E+01	3.36E+01

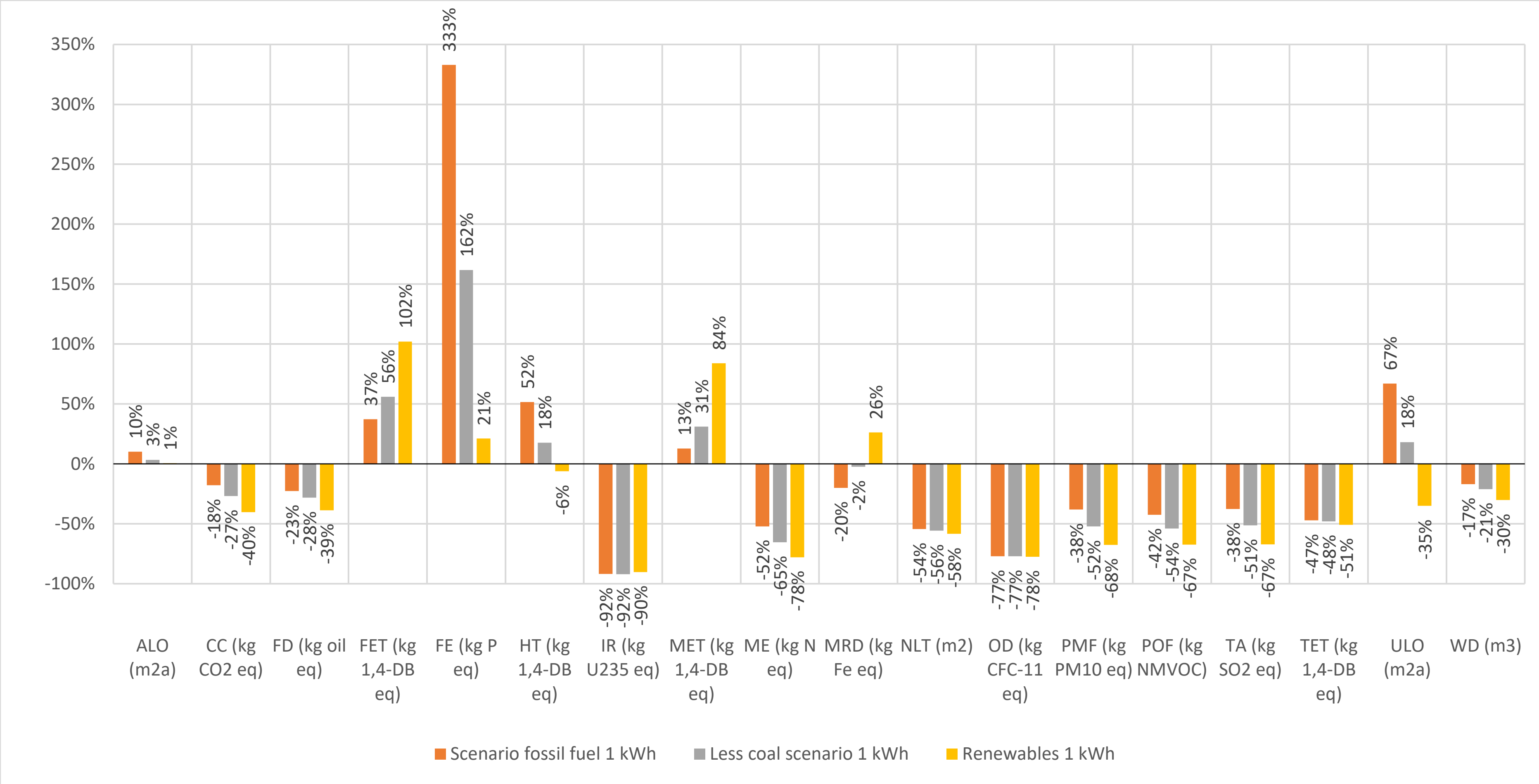
Appendix D – Supplementary material regarding alternative scenarios

D1 – Life cycle impact assessment of 1 kWh of electricity produced by different sources



- Oil has the highest impact per kWh in climate change (CC), fossil depletion (FD), natural land transformation (NLT), particulate matter formation (PMF), and terrestrial acidification (TA).
- Hard coal has the highest impact per kWh in freshwater eutrophication (FE).
- Wind has the highest impact per kWh in mineral depletion (MD).
- Wood chips has the highest impact per kWh in human toxicity (HT).

D2 – Life cycle impact assessment of 1 kWh of electricity production for the different scenarios



D3 – Endpoint indicators, contribution from climate change/freshwater eutrophication/freshwater ecotoxicity/marine ecotoxicity/human toxicity/fossil depletion/mineral resource depletion to the three endpoint indicators

Ecosystems (species.yr)							
Impact categories	**Baseline**	**Fossil fuel**	**Δ**	**Less coal**	**Δ**	**Renewables**	**Δ**
Climate change	128.94	111.70	-17.24	102.97	-25.97	90.09	-38.85
Freshwater eutrophication	0.118	0.152	0.033	0.134	0.016	0.120	0.002
Freshwater ecotoxicity	0.117	0.128	0.011	0.134	0.017	0.148	0.031
Marine ecotoxicity	0.022	0.023	0.001	0.024	0.002	0.027	0.004
			-17.19		-25.93		-38.81

Human health (DALY)							
Impact categories	**Baseline**	**Fossil fuel**	**Δ**	**Less coal**	**Δ**	**Renewables**	**Δ**
Climate change	22766	19722	-3044	18181	-4585	15907	-6859
Human toxicity	2849	3118	269	2941	92	2817	-32
			-2775		-4493		-6891

Resources ($)							
Impact categories	**Baseline**	**Fossil fuel**	**Δ**	**Less coal**	**Δ**	**Renewables**	**Δ**
Fossil depletion	8.52E+08	6.95E+08	-1.57E+08	6.57E+08	-1.96E+08	5.84E+08	-2.69E+08
Mineral resource depletion	2.00E+08	1.98E+08	-1.27E+06	1.99E+08	-1.53E+05	2.01E+08	1.65E+06
			-1.58E+08		-1.96E+08		-2.67E+08

Lola Sylvie Annie Rousseau

Environmental impact of railway development - The Standard Gauge Railway in Tanzania

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