LIFE CYCLE ASSESSMENT OF OFF-HIGHWAY TRUCKS AND BELT CONVEYORS FOR SUSTAINABLE MINING

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ABSTRACT

LIFE CYCLE ASSESSMENT OF OFF-HIGHWAY TRUCKS AND BELT CONVEYORS FOR SUSTAINABLE MINING

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In recent years increasing growth rate of all industrial fields generated an emerging energy demand and consequent environmental problems worldwide. Defining environmental profiles of products and systems using environmental tools, such as Life Cycle Assessment (LCA), is a critical issue for sustainable mining. In order to tackle the increasing environmental challenges and air emissions induced by surface coal mining, alternative material handling options are needed to be evaluated. This research study aims to provide a robust LCA model in selection of the alternative material haulage systems as a decision support system. The main objectives of this thesis study are: i) contributing to the national archived data by gathering data about haulage systems from an open pit coal mine, ii) constructing life cycle inventory from the acquired environmental data, iii) performing life cycle assessment of both material haulage systems in an open pit coal mine according to their environmental burdens, iv) conducting uncertainty assessment, and v) suggesting improvement in stages where emissions are critical. In order to accomplish these objectives, comparative LCA from cradle-to-grave was carried out in SIMAPRO 7.3 to determine life cycle environmental impacts of off-highway mining trucks and belt conveyors in coal transportation.

Climate change and acidification were selected as major impact categories considered to be major concerns in mining industry. The results of this study revealed that off-highway trucks had 1.9 times greater impact on acidification category than belt conveyors, on the other hand, belt conveyors had 1.6 times greater impact on climate change. NO_x emissions caused 96 percent of the acidification impact. CO_2 emissions from fossil fuel combustion led to 95 percent of the climate change effect. The obtained results also indicated that the highest impact on all selected impact categories were generated from the utilization stage of the trucks operated by diesel oil and utilization of belt conveyor systems operated by electricity.

The main novelty of this study is that it is one of the first LCA studies in the Turkish mining industry where considerable amount of emissions occur due to material handling. This study also advances the current knowledge about environmentally critical processes in material handling systems and places recommendations for both alternatives aiming better decision making. The results of the study are expected to provide a decision support system for the mining industry.

Keywords: Life Cycle Assessment, Material Handling, Off-highway Trucks, Belt Conveyors, Surface Mining

ÖZ

SÜRDÜRÜLEBİLİR MADENCİLİK İÇİN KAMYON VE BANTLI KONVEYÖRLERİN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

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Son yıllarda tüm endüstriyel alanlardaki artan büyüme hızı, dünya çapında yükselen enerji talebine ve buna bağlı çevresel sorunlara neden olmuştur. Ürün ve sistemlerin çevresel profillerinin Yaşam Döngüsü Değerlendirme (YDD) gibi çevresel araçlar ile tanımlanması, sürdürülebilir madencilik için önemli bir konudur. Açık ocak madenciliğinden kaynaklı artan çevresel sorunları ve emisyon sorunlarını ele almak amacıyla alternatif malzeme taşıma sistemlerinin değerlendirilmesi gerekmektedir. Bu çalışma, alternatif malzeme taşıma sistemlerinin seçiminde bir karar destek sistemi olarak güvenilir bir YDD modeli geliştirmeyi hedeflemektedir. Çalışmanın temel amaçları: i) bir açık ocak kömür madeninden malzeme taşıma sistemleri hakkında veri toplayarak ulusal arşiv verisine katkı sağlamak, ii) elde edilen çevresel veriden yaşam döngüsü envanteri oluşturmak, iii) bir açık ocak madenindeki malzeme taşıma sistemlerine çevresel yüklerine göre yaşam döngüsü değerlendirmesi yapmak, iv) belirsizlik değerlendirmesi gerçekleştirmek ve v) emisyonların ciddi düzeyde olduğu aşamalarda iyileştirmeler önermektir. Bu hedefler doğrultusunda kömür taşımacılığında kullanılan ağır yük kamyonu ve bantlı konveyörün çevresel etkilerini belirlemek amacıyla SIMAPRO 7.3 ile beşikten-mezara karşılaştırmalı YDD' si yürütülmüştür.

İklim değişikliği ve asitlenme, madencilik endüstrisinin temel kaygıları olarak ana etki kategorileri olarak seçilmiştir. Bu çalışmanın sonuçları, ağır yük kamyonlarının asitlenme kategorisinde bantlı konveyörlere göre 1,9 kat daha fazla etkiye sahip olduklarını, öte yandan, bantlı konveyörlerin ise iklim değişikliği kategorisinde 1,6 kat daha fazla etkiye neden olduklarını ortaya çıkarmıştır. NO_x emisyonları asitlenme etkisinin %96'sına neden olmuştur. Fosil yakıtların yanmasından kaynaklı CO_2 emisyonları iklim değişikliği kategorisinin %95'ine neden olmuştur. Elde edilen sonuçlar ayrıca seçilen tüm etki kategorilerinde en yüksek etkinin dizel yakıt tüketen kamyonların ve elektrik ile çalışan bantlı konveyörlerin kullanım aşamaları olduğunu göstermiştir.

Bu çalışmanın sahip olduğu temel farklılık, malzeme taşımacılığından kaynaklı önemli ölçüde emisyonların salındığı Türk maden endüstrisinde ilk YDD uygulamalarından birisi olmasıdır. Ayrıca çalışma sayesinde malzeme taşıma sistemlerinde çevresel açıdan önemli işlemler hakkındaki mevcut bilgi gelişmekte ve her iki alternatif için de daha iyi karar vermeyi amaçlayan öneriler sunulmaktadır. Çalışma sonuçlarının madencilik endüstrisi için bir karar destek sistemi sağlaması beklenmektedir.

Anahtar Kelimeler: Yaşam Döngüsü Değerlendirme, Malzeme Taşımacılığı, Ağır Yük Kamyonu, Bantlı Konveyör, Açık Ocak Madenciliği

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CHAPTER 1

INTRODUCTION

1.1 Background Information

Environmental impacts of continuous utilization of non-renewable energy resources are crucial more than ever. Total share of coal in Turkey's electricity production indicates the important role of coal in Turkey's energy industry as a primary energy resource. Coal production is now faced with increasing environmental constraints both in mining and utilization. It is vital to ensure that coal is mined and used in an economically efficient and ecologically sustainable manner especially in Turkey as a developing country (OECD, 2009) that cannot presently meet the regulations and costs of environmental protection completely.

In electricity generation, coal has a significant share of 28.98 percent as it is seen in Figure 1.1. Lignite is a primary energy source used especially in power plants. General Directorate of Turkish Coal Enterprises (TKI)[*] stated in their annual report of 2009 that Turkey's lignite reserves are approximately 12.3 billion tons and share of lignite in electricity production is 13.3 percent (TKI, 2009; Eurocoal, 2006). Therefore, environmental impact of lignite has major importance in Green House Gas (GHG) emissions of Turkey.

[*] General Directorate of Turkish Coal Enterprises (Türkiye Kömür İşletmeleri (TKI) Kurumu, in Turkish) is a state-owned enterprise that governs coal mining and marketing to provide Turkey with coal products according to the national energy policy.

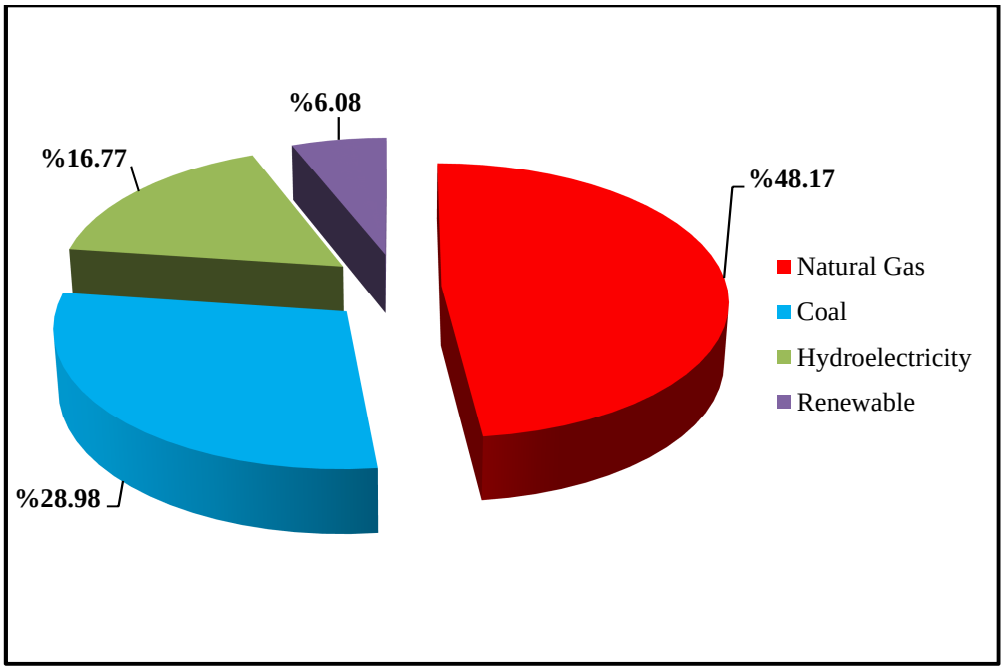


Figure 1.1 Electricity production in Turkey (TKI, 2009)

In February 2009, Turkey became signatory to the Kyoto Protocol, and therefore, needed to come up with policies for cleaner development supported by external sources of finance. Implementing new technologies targeting reduction of emissions will be obligatory in the future as Turkey's primary energy source is coal. Implementation of an approach with that aim such as Life Cycle Assessment (LCA) is significant in mining industry and other sectors. As coal is produced in Turkey, it has major importance for energy and mining sectors as the primary energy source due to the amount of lignite reserves.

Mining is a high majority industry supplying raw material and energy to various sectors. Thus, emissions generated by the mining industry have a critical share and major importance in Turkey's GHG emissions. Ministry of Environment and Forestry stated in the First National Communication on Climate Change that 76.7 percent share of total GHG is originated from the energy sector as it is seen in Figure 1.2.

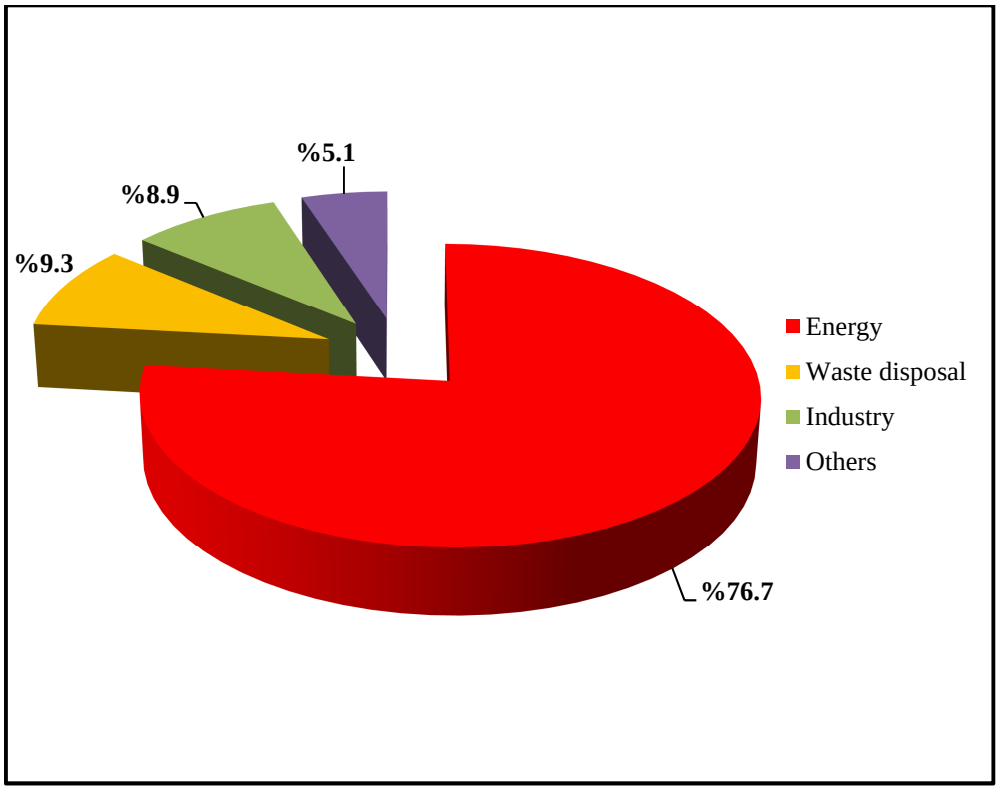


Figure 1.2 GHG emission of Turkey by sectors (MENR, 2010)

Environmental load of energy sector could be determined by utilizing LCA. LCA can be defined as a methodology that comprises the evaluation of the environmental effects produced during a product's entire life cycle, from its origin as raw material until its end, usually as a waste (Sonnemann *et al.*, 2004). LCA is a powerful tool to assist economic analysis in decision making in any kind of production process.

1.2 Statement of the Problem

Coal is an essential resource for Turkey and will be certainly extracted in the future with an increasing production along with development in every industry. As this is inevitable, determination of major environmental burdens and their utilization in decision making becomes more important. Coal mining has a major role in Turkey's primary energy generation where environmental data could be utilized as

a supportive decision making criterion. Equipment comparison is a decision making process where environmental load generated from energy consumption could be utilized.

Emissions in energy industry, especially in mining reached a critical stance due to the increasing production, and hence, common utilization of high capacity equipment. Material handling has a major role for mining as it is an essential stage of the basic production cycle. Produced ore and overburden material is handled either by haulage or hoisting equipment with considerable fuel consumption. Therefore, researches about environmental impacts of material handling systems in a quantitative manner will aid cleaner coal production. Off-highway trucks and belt conveyors are the most commonly utilized transportation systems in surface coal mines which are represented in Figure 1.3.

Figure 1.3 Off-highway truck and belt conveyor (MTN, 2011)

Regulations and internationally accepted standards will force mining industry to employ environmental load as a supportive criteria in decision making and equipment selection. Therefore, methodologies such as LCA will be utilized more

commonly in the mining industry. Environmental burden of material handling systems is still not utilized as data in any kind of decision making process in Turkey. Conventional equipment selection is based on productivity and economic figures. Sustainable mining could be supported by utilization of environmental data throughout mine management decisions.

In order to see and improve the current situation of mining in Turkey, indicators of sustainable development should be determined. Sustainable development indicators measure the progress made in sustainable growth and development. By this way, it is possible to determine the sustainability performance of ongoing mining operations and their share in the sustainable development targets of Turkey. Sustainable mining in Turkey can only be achieved by using methodologies such as LCA in determination of sustainability indicators starting with material handling where fossil fuels and electricity are used intensively.

1.3 Objectives and Scope of the Study

The main objective of this research study is to compare belt conveyors and trucks for haulage in an open pit coal mine using LCA with respect to their GHG emissions. Elements of this objective can be listed as:

i. Gathering data about haulage systems from an open pit coal mine,
ii. Constructing life cycle inventory from the acquired environmental data,
iii. Analyzing both material haulage systems in an open pit coal mine according to their environmental burdens,
iv. Conducting uncertainty assessment, and
v. Suggesting improvement in stages where emissions are critical.

Although haulage of material in mining industry causes pollution in soil, water, and air, scope of this study is narrowed down to air pollution that will be considered by

GHG emissions. Major impact categories that are discussed as a result of the comparison study are climate change and acidification. Boundaries of the systems under consideration are covering manufacture and utilization, whereas end of life processes, such as incineration and recycling are excluded from the LCA comparison due to data gaps in these fields.

1.4 Research Methodology

In this study, the environmental effects of off-highway mining trucks and belt conveyors in an open pit coal mine are studied using LCA. Upstream and downstream processes for both material handling systems were determined and environmental data was gathered from Eco-invent database integrated in SIMAPRO software (Pre, 2011) as there is no publicly available emission database specifically prepared for mining industry in Turkey. Data was modified according to information gathered from engine manufacturer, governmental institutions, and TCE.

Environmental load of both material handling systems were determined and compared. A common technically equivalent basis is determined in order to compare both systems that are modeled as manufacturing and utilization in SIMAPRO software. Off-highway mining trucks and belt conveyors are compared according to all possible categories; however, major impact is evaluated according to acidification and climate change because major concerns of mining industry originate from the energy consumption. Since the primary data source was derived from the modification of Eco-invent database, available uncertainty in the data was assessed by uncertainty assessment using Monte Carlo Simulation. A life cycle assessment software, SIMAPRO (Pre, 2011) was used for the comparison and the uncertainty assessment of the comparison in selected impact categories. In addition to this, uncertainty assessments of GHG emissions were also conducted by Monte Carlo Simulation tool in SIMAPRO.

1.5 Outline of the Thesis

This thesis is composed of five chapters. In the first chapter, general information was presented about the thesis and problem. In Chapter 2, concept of LCA and literature review about LCA applications in various industrial fields were presented. In Chapter 3, comparison of off-highway mining trucks and belt conveyors was presented in detail following main stages of LCA. In Chapter 4, the results of the comparison were summarized. In the last part, Chapter 5 conclusions and recommendations were given.

CHAPTER 2

LITERATURE REVIEW

LCA is a tool that can be used to evaluate the environmental performance of products and services and it focuses on the entire life-cycle, from the extraction of resources and processing of raw material to recycling. There are four main stages that are followed in LCA studies. First, main objectives are stated and functional unit, basis of the LCA analysis, is defined in detail in goal and scope definition. Besides, system boundary between the functional unit and the environment is identified in this stage. Data for processes and materials utilized for representation of the product or system is collected and organized in inventory analysis stage. Then, results of the LCA study are presented according to chosen impact categories in impact assessment stage. Finally, a report is prepared in accordance with ISO 14040 standard to present results to target audiences. In this chapter, an introduction to LCA methodology and an extensive literature review about LCA applications is presented. The literature review about LCA is focused not only specifically to the mining industry but also on other application areas due to the fact that the basic approach to the problem is the same regardless of industry. After critical overview of LCA in Turkey is given, rationale of this research study is stated.

2.1 Definition of Life Cycle Assessment (LCA)

LCA of a product or system comprises the evaluation of the environmental effects produced during its entire life-cycle, from its origin as a raw material until its end, usually as a waste as defined by Sonnemann *et al.* (2004). The ISO 14040 standard defines an LCA as a compilation and evaluation of the inputs and outputs and the

potential environmental impacts of a product system through its life cycle (ISO 14040, 2006). LCA identifies and quantifies releases into air, water, and soil during extraction and consumption of resources (Curran and Young, 1996). Potential impact contribution of these resources' extraction and consumption, as well as environmental releases causing several important types of environmental impacts, is assessed and evaluated.

LCA has a unique multidisciplinary character that covers technical and social aspects. Environmental mechanisms indicating the effect of an emission are inevitably hard to analyze as it is challenging to simulate a condition that has a relatively long time extension such as climate change. LCA studies can also be considered to collaborate with social sciences as subjective choices have to be made, such as weighting.

LCA is based on the International Standard EN ISO 14040, documentation and technical guidelines. ISO is a non-governmental organization that forms a bridge between the public and private sectors. On the one hand, many of its member institutes are part of the governmental structure of their countries or are mandated by their government. On the other hand, other members have their roots uniquely in the private sector, having been set up by national partnerships of industry associations. ISO enables a consensus to be reached on solutions that meet both the requirements of business and the broader needs of a society.

A major source of basic information about LCA is the Society for Environmental Toxicology and Chemistry (SETAC) founded in 1979, a multidisciplinary society of professionals with industrial, public and scientific representatives. One of SETAC's goals is the development of LCA methodology and criteria so that publications of this institution could be planned and studied.

According to the international standard ISO 14040, LCA consist of four main stages as illustrated in Figure 2.1. As it is stated in ISO 14040, LCA studies are recommended to follow this guideline.

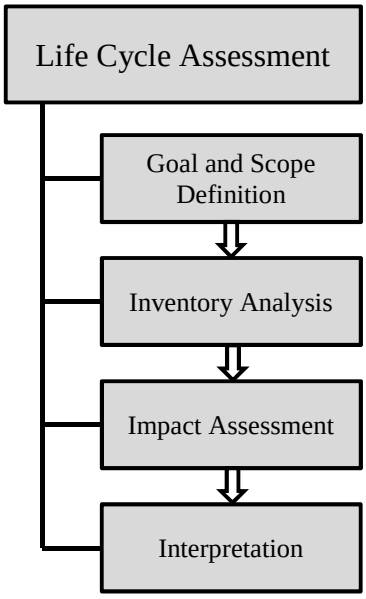


Figure 2.1 LCA Framework

First stage of LCA is goal and scope definition where the problem is defined in detail. Then, background data about processes and materials in the scope of the study are utilized to generate an inventory. Analysis is conducted according to selected impact categories and finally results are presented in the interpretation stage.

2.1.1 Goal and Scope Definition in LCA

The goal and scope definition part defines the required specifications and identifies the problem to be handled in detail. Subject of the study, functional unit, which is a quantitative reference, is defined. Functional unit definition has a key importance in LCA as an initial part of these four major stages founding a basis especially in case of comparison studies. Unit functions are defined in detail prior to data collection

and boundary definition. In order to efficiently compare technically equivalent equipment, products or production techniques, functional unit has to be predefined.

In order to narrow down the subject, a boundary between the functional unit and the environment should be determined. Relative Mass-Energy-Economic (RMEE) method can be considered as an adaptable approach in minerals industry and is based on threshold values (Raynolds *et al*., 2000). It is used to compare inputs to the system. If this ratio of input to functional unit is less than a selected cut-off then the input will be excluded from the analysis and all unit processes, upstream of that input, will be left outside the system boundary.

Drawing the line between functional unit and environment points out the limits of the system under consideration. In order to make preliminary assumptions for input and output to the environment, a flowchart indicating all unit processes should be prepared. Environmental burden caused by these unit processes is obtained from data collected or gathered from databases so that required details could be clarified in the goal and scope definition stage.

2.1.2 Inventory Analysis in LCA

Life Cycle Inventory (LCI) is considered as a stage in which all the environmental loads or environmental effects generated by a product or activity during its life cycle are identified and evaluated. During the inventory analysis, all the data of unit processes are collected in relation to the functional unit. Although publicly accessible databases, such as World Bank, Turkish Statistical Institute (TSI), and International Energy Agency (IEA) are sufficient to cover many of the industrial processes, there are cases that readily available or obtained data is not representative. This is a commonly encountered challenge in the mining industry. In order to tackle this problem, the missing data is collected and then classified according to its propriety to the case, thus, studies in mining industries require foreground data.

Data collection is considered as a critical stage especially in cases where publicly accessible databases are not present. Turkey has no national database for emissions or environmental effects which considers mining industry in detail. Data reviews revealed the fact that available data-sets could be utilized to represent Turkey on country basis, however this may cause uncertainties in smaller scale studies. As it is represented in Figure 2.2 and Figure 2.3, data gathered from the World Bank about Turkey's electricity generation, methane (CH_4), and nitrogen oxide (NO_x) emissions there is no distinct classification for industrial fields such as mining. Utilization of such data is not preferred due to the inherent uncertainty.

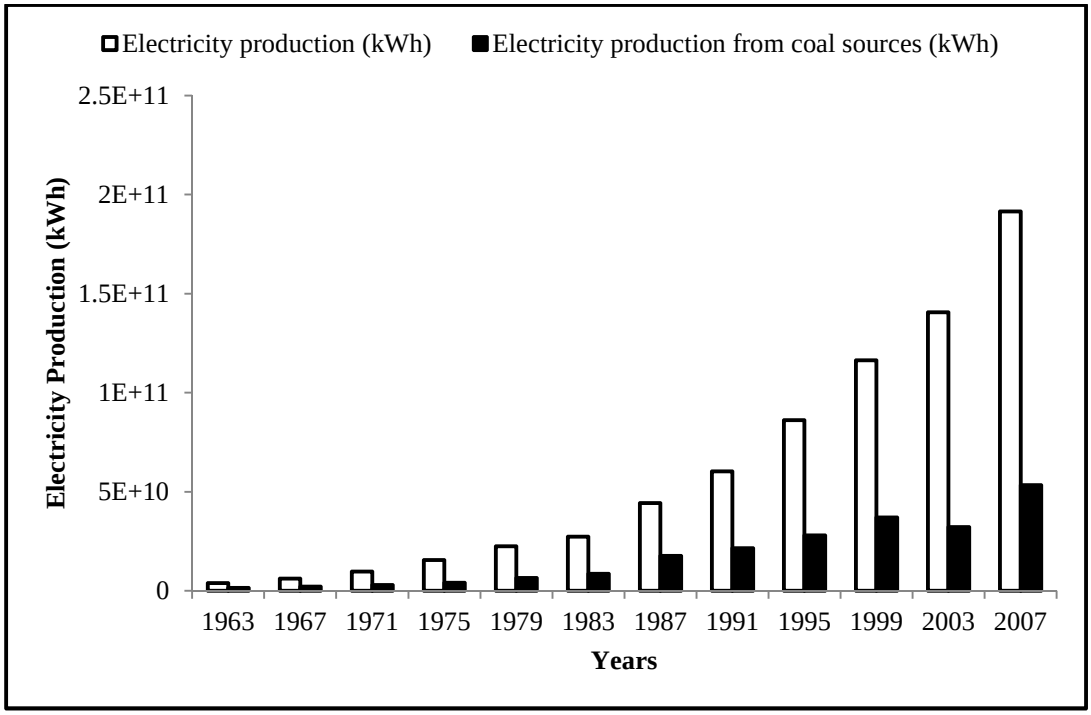


Figure 2.2 Annual electricity production of Turkey and share of coal (World Bank, 2006)

Electricity production has an increasing trend from 1963 to 2007 in Turkey. This can be explained by the developing industry and increasing energy requirement. Share of coal in the electricity production is observed as increasing until 1990s. After 1990, although renewable energy alternatives started to take share in the electricity grid, coal still sustained its critical role in electricity production.

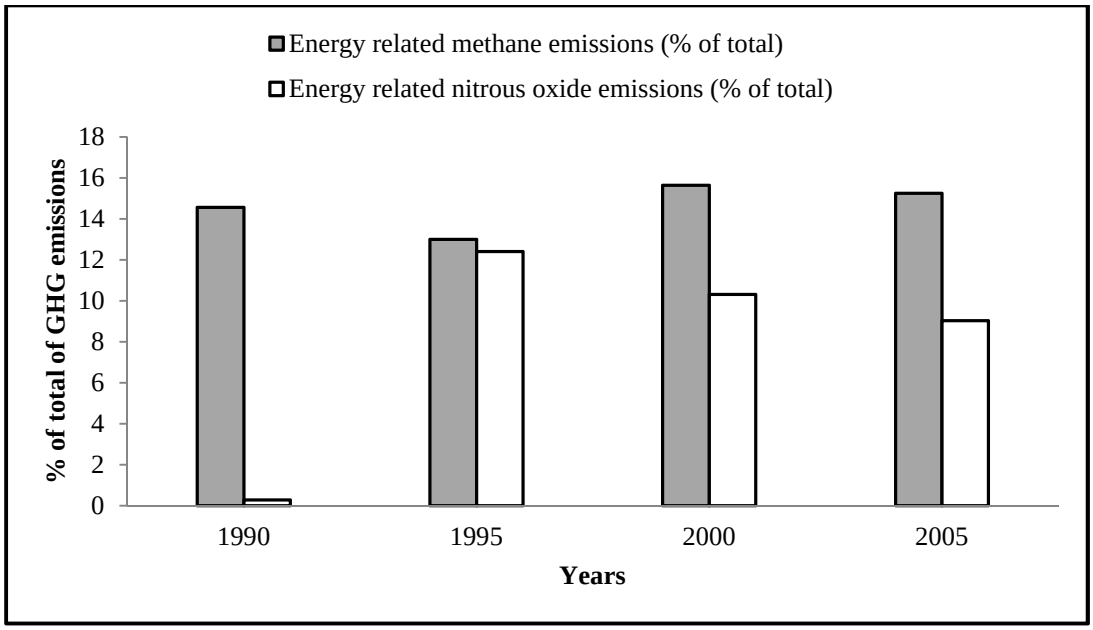


Figure 2.3 Energy related methane and nitrogen oxide emissions (World Bank, 2006)

Energy related CH_4 emissions increased from 1995 to 2000, whereas, NO_x emissions decline starting from 1995. Petroleum and its products were not preferred for electricity production due to the increasing utilization of natural gas and other energy resources. Thus, NO_x emissions originated from fossil fuel burning power stations decreased. Constant rate of CH_4 emissions from 2000 to 2005 also indicate that coal maintained its major role in energy generation.

Quality of gathered data affects representativeness of LCA studies and consistency of results. For instance, there are methodologies for estimation of emissions such as Intergovernmental Panel on Climate Change (IPCC). IPCC methodology is based on emission estimation based on fuel consumption. Such estimations might cause uncertainty or data gaps in modeling of products or processes in LCA studies. Estimation of environmental data is commonly utilized in description of environmental profiles of countries. As it is presented in Figure 2.4, TSI prepared an inventory categorized into energy, industrial processes, agricultural activities, and waste pointing out the major share of energy in Turkey's emissions.

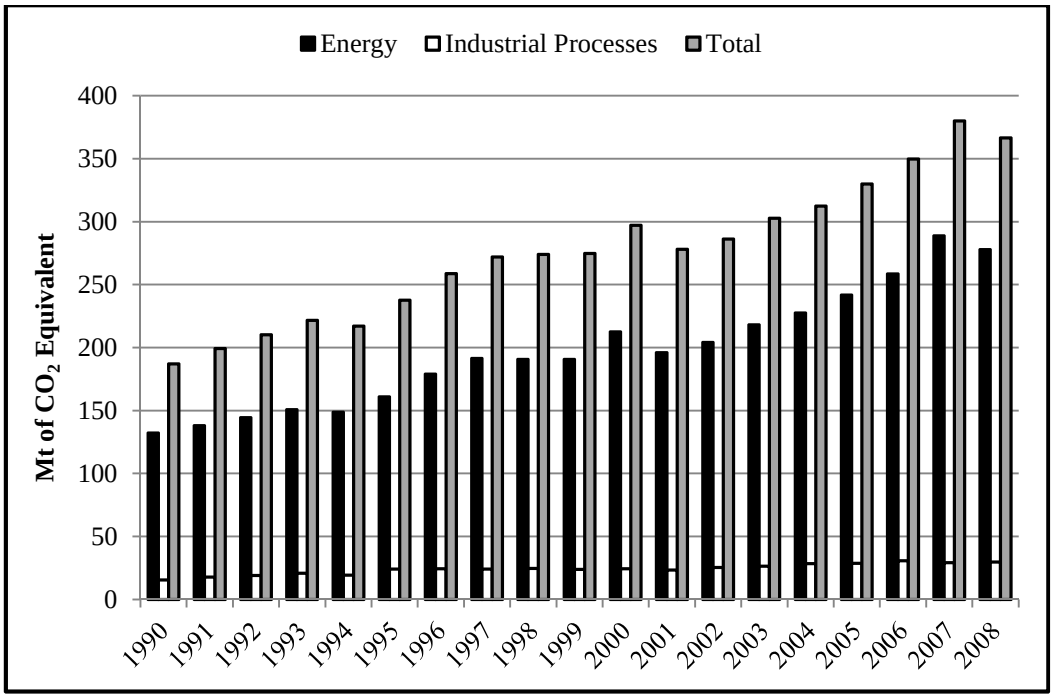


Figure 2.4 Sectoral GHG emissions of Turkey (TSI, 2008)

Energy industry comprises majority of GHG emissions in Turkey. Emissions of industrial processes are observed as lower when compared to energy industry. This might be caused by misrepresentation of GHG emissions for industrial processes where metadata about the scope of industrial processes was missing.

GHG emissions are dominated by CO_2 as it is seen in Figure 2.5. It is also observed that general trend of emissions in years is distinctly directed by CO_2 (Figure 2.5). CH_4 emissions have a constant trend without reaching any peak values between 1990 and 2008. Correlation between CO_2 emissions and total GHG emissions can be seen from the similar trend (Figure 2.5). This also indicates the dominating impact of CO_2 on total GHG emissions. The inclining tendency in GHG emissions can be explained by energy requirement of Turkey. Development in all industrial fields extended the range of energy consumption and related GHG emissions such as nitrous oxide (N_2O), NO_x, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOC).

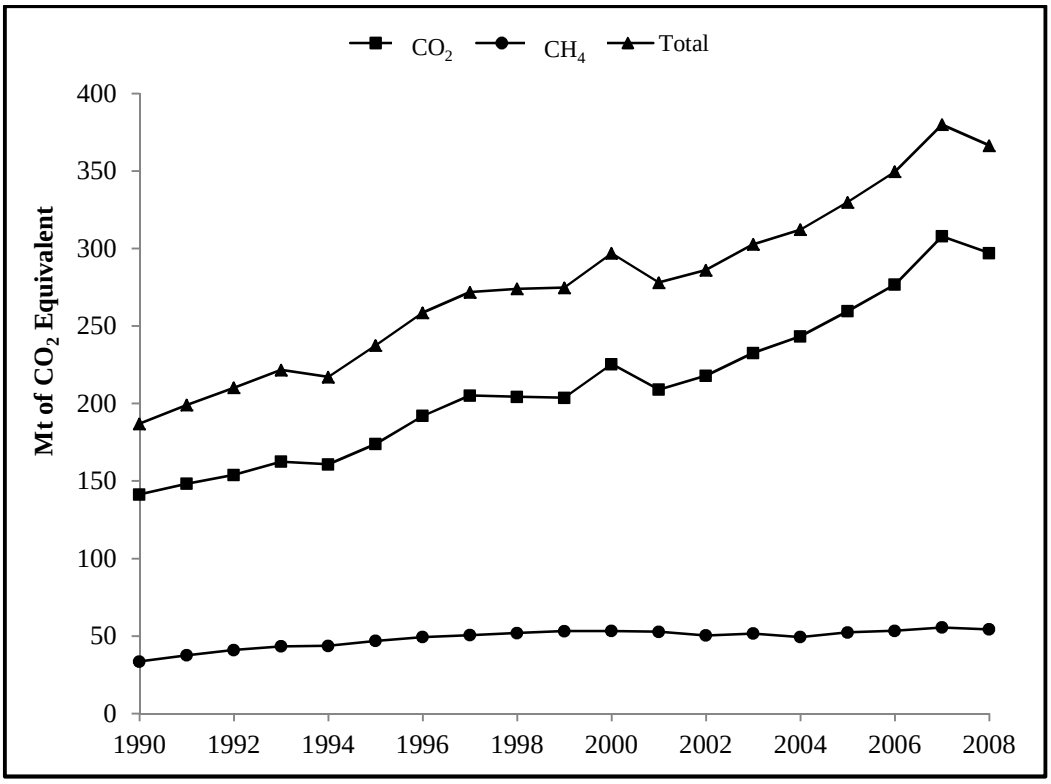


Figure 2.5 GHG emissions of Turkey (TSI, 2008)

Emissions from 1990 to 2008 are represented as million tons of CO_2 equivalent. Utilization of data published by TSI in LCA studies may not be possible due to lack of detail in metadata and potential of misleading results. In addition to CO_2, and CH_4, other emissions such as N_2O, NO_x, CO, and NMVOC from various industrial sources from 1990 to 1999 are represented in Appendix-A (Table A1-6).

IEA is another institution that published data for Turkey's emissions (IEA, 2010). Energy consumption and fuel combustion related CO_2 emission of Turkish coal industry are summarized in Table 2.1. As it is stated, Turkey initiated its IEA reporting in 2008, thus, data about energy consumption and CO_2 emissions from fuel combustion is recorded for a single year except for electricity consumption.

Table 2.1 Energy consumption and fuel combustion related CO_2 emission of Turkish coal industry (IEA, 2010)

Energy Consumption (ktoe)									
Flow	Coal mines								
Country	Turkey								
	2000	2001	2002	2003	2004	2005	2006	2007	2008
Coking coal	--	--	--	--	--	--	--	--	19.4
Other bituminous coal	--	--	--	--	--	--	--	--	1.9
Lignite/brown coal	--	--	--	--	--	--	--	--	31.7
Electricity	46.6	39.3	38.4	38.4	39.0	40.5	41.9	46.5	47.1
Total	46.6	39.3	38.4	38.4	39.0	40.5	41.9	46.5	100.1

CO_2 Emissions from Fuel Combustion (kt CO_2)									
Flow	Coal mines								
Country	Turkey								
	2000	2001	2002	2003	2004	2005	2006	2007	2008
Coking coal	--	--	--	--	--	--	--	--	71.7
Other bituminous coal	--	--	--	--	--	--	--	--	7.5
Lignite/brown coal	--	--	--	--	--	--	--	--	131.7
Total	--	--	--	--	--	--	--	--	210.9

Besides these publicly available databases, there are other databases integrated to various commercial programs that can be used in LCA. One of these databases is Eco-invent database integrated to SIMAPRO (Pre, 2011) program.

Eco-invent Database: Publicly available data is not preferred for LCA studies by means of data quality, and thus, complete data-sets are more commonly used. Eco-invent is a comprehensive database embedded in the SIMAPRO software (Pre, 2011) with detailed data for various industrial processes. All impact categories defined in ISO 14044 are covered within the database for upstream and downstream processes. Naming of elementary flows in Eco-invent is guided by the SETAC working group "Data availability and data quality" (de Beaufort-Langeveld *et al.*, 2003; Hischier *et al.*, 2001). New substance names are recommended according to the related Chemical Abstract Service (CAS) numbers, sum formulas and International Union of Pure and Applied Chemistry (IUPAC) names. Unit processes are defined by their name, unit, and categories as summarized in Table 2.2.

Table 2.2 Categories and sub-categories in Eco-invent (Frischknecht *et al.*, 2007)

Category	Subcategory	Definition	Assigned in general to
air	low population density	Emissions in areas without settlements or protected areas in the direct surrounding	Resource extraction, forestry, agriculture, hydro energy, wind power, coal, and nuclear power plants, municipal landfills, wastewater treatment, long-distance transports, shipping
	low population density, long-term	Emissions which take place in the future, 100 years after the start of the process.	Emissions from Uranium mill tailings.
	lower stratosphere + upper tropo-sphere	Emissions from air planes	Air transport cruises.
	high population density	Emissions near settlements or pro-tected areas which affect directly people or animals due to the local situation. Important for particles.	Industry, oil and gas power plants, manu-facturing, households, municipal waste in-cineration, local traffic, construction processes.
	unspecified		Only used if no specific information available.
resource	in air	Resources in air, e.g. Argon, carbon dioxide	Used for carbon uptake in biomass and gases produced by air separation.
	biotic	Biogenic Resource, e.g. wood	
	in ground	Resource in soil e.g. ores, but also for landfill volume	
	land	Land occupation and transformation	
	in water	Resource in water, e.g. magnesium, water	
soil	agricultural	Emission to soil used for the production of agricultural products	Agriculture
	forestry	Emission to soil used for plant production (forest, renewable raw materials) which do not enter the human food chain,	Forestry
	industrial	Emission to soil used for industry, manufacturing, waste management, and infrastructure.	Industry, land farming of wastes, built-up land.
	unspecified		Only used if no specific information available,
water	ground-	Ground water which will get in contact with the biosphere after some time.	
	ground-, long-term	Emissions which take place in the future, 100 years after the start of the process.	Long-term emissions from landfills
	lake	Lakes with sweet water	
	ocean	Ocean, sea, and salty lakes.	Offshore works, overseas ship transports.
	river	Rivers	Discharge of effluents from wastewater treatment facilities.
	river, long-term	Emissions which take place in the future, 100 years after the start of the process.	Long-term emissions; subcategory not used in Eco-invent database
	fossil-	Salty ground water that does not get into contact with the biosphere.	Re-injection of formation water from oil- and gas extraction; subcategory not used in Eco-invent database
	unspecified		Only used if no specific information available.

Inventory data is commonly generated as national averages and this prevents representation of spatial differences in data. Eco-invent refer to abbreviations for countries, continents, and international organizations to define data for unit processes. Although comprehensive data for unit processes is present, there are still concepts where data gaps are present. For instance, noise emissions are not available in Eco-invent as there is no standardized reporting method yet. Likewise water vapour, nitrogen, oxygen releases to air, and combustion air are not recorded as an input.

Emissions in the air category with dominant share in certain impact categories are identified in detail. There is no distinction defined for fossil and biogenic CO_2, CO, and CH_4 in the database. Biogenic CO_2 related to renewable energy sources is recorded separately. CH_4 and NMVOC emissions are accounted distinctly because of their effect on climate change impact category. Sulphur oxides (SO_x) and NO_x emissions are reported as SO_2 and NO_2 respectively. Information about sulphure trioxide (SO_3) or sulfate (SO_4), and nitric oxide (NO) emission shares in the total amount emission is also given. In addition to airborne emissions, Eco-invent database contains detailed pollutant information for water and soil, such as biological oxygen demand for five days (BOD5) for carbon compounds in water or pollutants in agricultural areas in soil.

Besides pollutants and their effect on the environment, energy and resources are commonly utilized in LCA studies. Eco-invent database accounts energy produced by different technologies by their equivalent share on converted energy whereas the extraction of metals and other minerals in ores is recorded as the amount of target material that is contained in the ore. Data about resources in Eco-invent database is directly related to minerals industry and is taken into account in upstream and downstream processes. Certain assumptions are determined for each ore for naming purposes as it is seen in Table 2.3 with some examples.

Table 2.3 Examples for the naming of ore resources' elementary flows (Frischknecht *et al.*, 2007)

Elementary Flow	**Meaning of the flow**
1kg Magnesite, 60 % in crude ore, in ground	Extraction of 1 kg magnesite ($MgCO_3$ or 286 g magnesium) in 1.67 kg crude ore.
1 kg Aluminium, 24 % in bauxite, 11 % in crude ore, in ground	Extraction of 1 kg aluminium in 4.17 kg bauxite, in 9.1 kg crude ore.
1 kg Nickel, 1.13 % in sulfide, Ni 0.76 % and Cu 0.76 % in crude ore, in ground	Extraction of Nickel from a Nickel-Copper mine with a Nickel (and Copper) content of 0.76 % (each) in the crude ore.

Another data category commonly discussed is land occupation and land transformation. Although there is no complete data-set for the land occupation and land transformation data in any industrial field, Eco-invent defined major impact on natural resources, natural environment, and man-made environment. Main differences between land occupation and land transformation are defined in the database. Land occupation is identified by square meters times time (m^2a) as the duration of required production is important. Land transformation links a state during an economic activity with a state before, during, and after that activity. Although Eco-invent database can be used for comprehensive LCA studies, an alternative data generation method, IPCC can also be utilized in case of studies only considering airborne GHG emissions.

IPCC Methodology: The IPCC methods are developed to estimate and report on national inventories of anthropogenic GHG emissions and removals. The methods are the primary technical guidelines for the national inventories, for instance Turkey. Turkey has become signatory to the Kyoto Protocol and initiated the national emission reporting.

Reports to represent national emissions are prepared and published according to the structure declared by IPCC in Figure 2.6 (Eggleston *et al.*, 2006). There is a hierarchic organization supported by peer-reviews of experts. Reports are reviewed and approved by the government prior to publication.

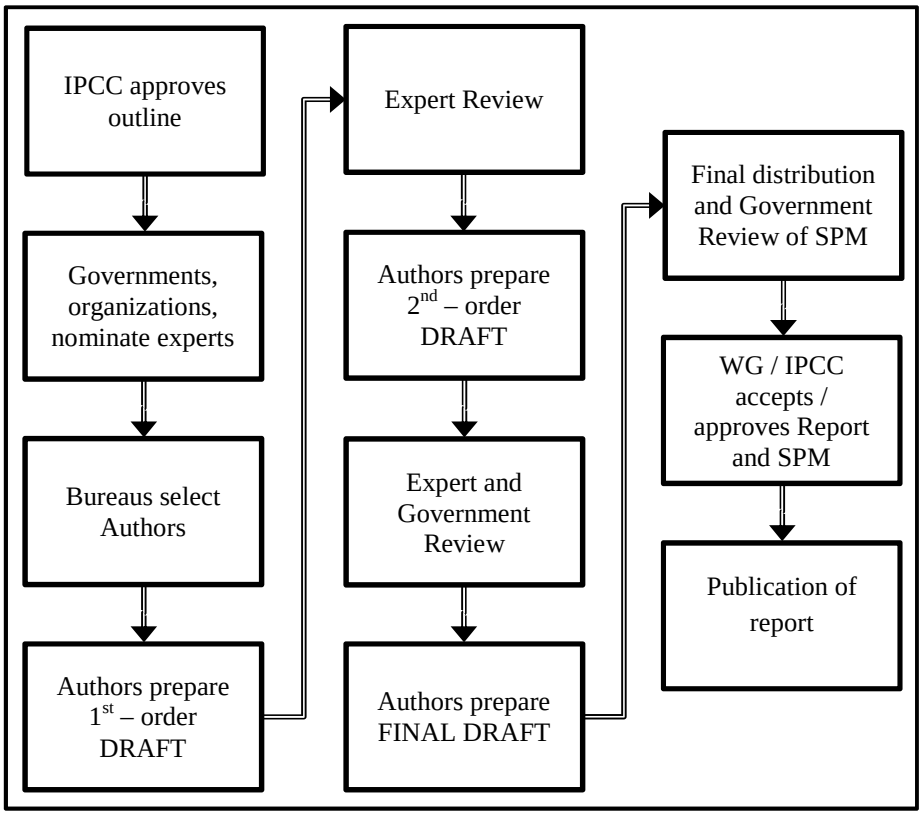


Figure 2.6 IPCC report methodology (Eggleston *et al.*, 2006)

The IPCC provides a common structure to categorize sources and sinks. This common structure is essential to compare the inventories and to avoid double counting problems. The activities that are not anthropogenic in origin or do not result in a net source/sink of GHG emissions are intentionally excluded from the inventories. Volcanic eruptions, carbon dioxide uptake or release by oceans, natural forest fires and human induced land use changes are the activities that are not anthropogenic. The main reasons for excluding these activities from inventories are the insufficient scientific understandings and the data were not adequately available to make calculations.

Tiers represent level of methodological complexity. There are three tiers in IPCC among which Tier-1 is stated as the basic approach (Eggleston *et al.*, 2006). Tier-2 and Tier-3 utilize decision trees besides estimations for key category identification. Tier-3 is the most demanding method in terms of complexity and data requirements. Main stages of estimating emission from fuel consumption by IPCC Tier-1 methodology is summarized in Figure 2.7 (Eggleston *et al.*, 2006).

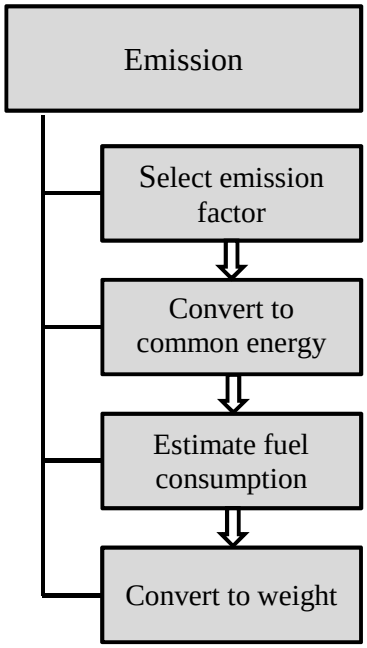


Figure 2.7 IPCC methodology Tier-1 (Eggleston *et al.*, 2006)

An example of Tier-1 calculation is represented in Table 2.4 (Can, 2006). The amount of diesel oil (tons) is first converted to tons of oil equivalent (toe) by multiplying it with the relevant factor. Then, results are converted to energy units before emission factors are used. In case of CO_2, there is an assumption stated by the IPCC methodology that carbon oxidized from the combustion of diesel oil is in the range of 99 percent (Eggleston *et al.*, 2006). As a result, amount of CO_2 emission is obtained after applying a ratio of the molecular weight of carbon (C) to oxygen (O).

Table 2.4 CO_2 emission derived from diesel oil consumption (Can, 2006)

Fuel Type	Unit	Fuel	Ton of Oil Equivalent Factor	TOE
		A	**B**	**C=A*B**
Diesel Oil	tones	119,122	1.02	121,504.58

Energy (Kcal)	Energy (Tjoule)	Carbon Emission Factor (tC/TJ)	Carbon Oxidized	Convert to CO_2 emission (tones)
$D=C*10^7$	**$E=D*4.184*10^{-9}$**	**F**	**G**	**J=E*F*G*44/12**
1,215,045,783	5,083.75	20.2	0.99	3,727,71.17

Although there are three main tiers used for emission determination, Turkey uses Tier-1 based only on fuel consumption. Tier-2 and Tier-3 require source specific data, such as, results of chemical analysis of fossil fuels. United Nations Framework Convention on Climate Change (UNFCCC) declared that there should be improvement in data quality for Turkey who started to prepare its inventory in 2006. Despite missing fields, Turkey is encouraged to utilize more sophisticated Tier methods in the report.

2.1.3 Impact Assessment in LCA

Impact assessment phase makes the results from the inventory analysis more understandable and more manageable in relation to human health, availability of resources, and natural environment. There are certain impact categories that are commonly used according to the subject of the study. Each category has a relevant common unit that has to be applied to the results to obtain the environmental profile of the subject.

Developed impact assessment methodologies are accepted internationally and utilized in every LCA study. It is preferred to select a category that has been published and is verified internationally.

Most commercial programs provide LCA practitioners with selected categories which can also be refined if necessary. Impact assessment is supported by goal and scope definition that shapes the desired aggregation level of the results depending on the target audience. Presentation of results to the target audience is mainly formed by the selected categories in impact assessment stage.

Life cycle impact assessment is defined as the phase in the LCA where understanding and evaluating the magnitude and significance of the potential environmental impacts of a product or system is aimed. There is a distinct identification about obligatory elements and optional elements followed in the impact assessment. Obligatory elements are stated as: (i) classification and (ii) characterization that have to be conducted in every LCA study. Optional elements in the impact assessment stage are defined as: (i) normalization, (ii) ranking, (iii) grouping, and (iv) weighting.

Selection of impact categories is aided by the definition of endpoints as presented in Figure 2.8. Endpoints are classified in terms of environmental concern, like human health, extinction of species, and availability of resources for future generation. It is not directly recommended by ISO to use end-points in LCA studies, however, clear description of links between the environmental model and the impact category aids selection of impact categories. Defining the link quantitatively is not obligatory, however, it is commonly preferred to describe the relation between mid-point and end-point categories in detail.

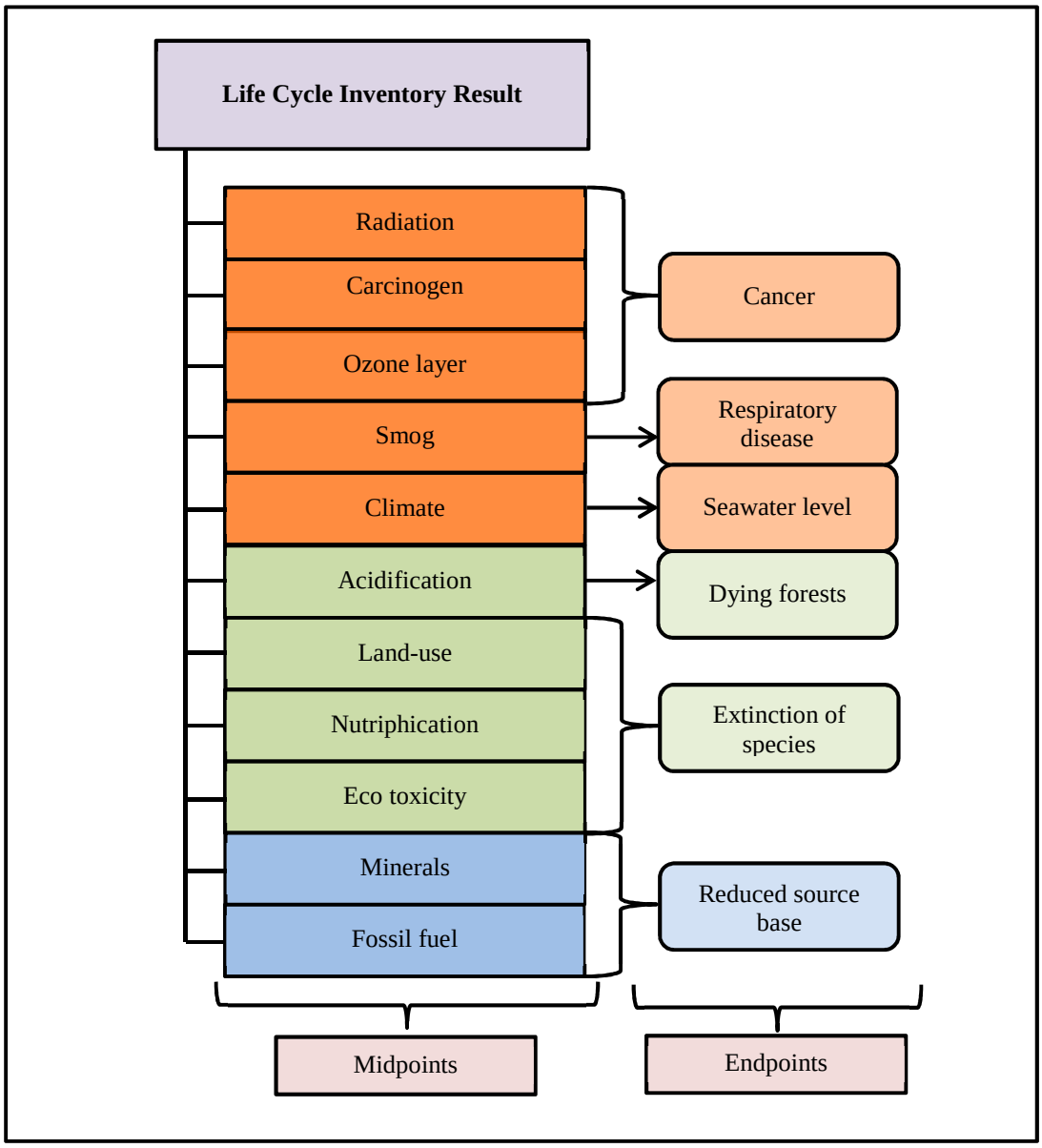


Figure 2.8 General overview of the structure of an impact assessment (Pre, 2008)

The obligatory elements characterization and classification should be conducted in the impact assessment. Characterization factors are defined after impact categories are selected and LCI results are assigned to these impact categories to reflect relative contribution of an LCI result to the indicator result. For example, on a time scale of 100 years the contribution of one kg CH_4 to global warming is 42 times as high as the emission of one kg CO_2. This means that if the characterization factor of

CO_2 is one, the characterization factor of CH_4 is 42. Thus, the impact category indicator result for Global Warming Potential (GWP) can be calculated by multiplying the LCI result with the characterization factor. Mid-point indicators, which are closer to the emission (Figure 2.8) with lower uncertainty, such as CML 92 are also allowed to be utilized in LCA studies by ISO. CML 92 is a mid-point methodology developed by the Centre of Environmental Science, University of Leiden where indicators are chosen close to the emissions (Frischknecht *et al.*, 2007). In the CML 92, IPCC equivalent factors are selected as a basis for ozone layer depletion and global warming impact categories. Acidification impact is estimated by emitted number of H^+ protons and is represented by kg SO_2 equivalent. Global warming potential is based on kg CO_2 equivalent emission.

Eco-indicator 99 is a more commonly utilized impact category. In Eco-Indicator 99, climate change is expressed in Disability Adjusted Life Years (DALY). This is a unit used by the World Health Organization (WHO) and World Bank to evaluate health statistics. Acidification is expressed in the percentage of decreased biodiversity over an area during a certain period. These indicators are calculated by considering the complete environmental model with certain assumptions. Eco-indicator is advantageous in interpretation as indicator categories might be presented more easily to target audiences. After completing obligatory stages, optional stages can be handled.

Optional stages that are described in ISO 14040 standards are normalization, ranking, grouping, and weighting. Normalization is a procedure that determines the contribution of an impact category to the environment. This is done by dividing the impact category indicators by a normal value which is commonly selected as the population of a country. Another common procedure is to determine the impact category indicators for a region during a year and divide this result by the number of inhabitants in that area. Grouping and ranking is used in LCA studies in order to prevent weighting, which is not recommended in comparisons of products or systems. As weighting sets are based on expert view, objectivity of comparisons

might be affected in case weighting is applied. Therefore, peer reviews are preferred in LCA comparisons of products that are presented to public audiences. Optimum environmental relevance is reached by grouping numerous indicator categories into one of the three end-point categories namely human health, ecosystem quality, and resources in Eco-invent database. After grouping, the last optional stage, weighting is considered as controversial and difficult, because expert view of a control group is utilized intensely.

2.1.4 Interpretation of LCA Results

The interpretation phase aims to evaluate the results from the inventory analysis or impact assessment and compare them with the goal of the study defined in the first stage. Important results should be identified and outcomes should be evaluated by sensitivity analysis or consistency checks. Recommendation and critical review of the subject should be included in the final report of the results. ISO 14040 standard defines how an LCA study should be presented to the target audience by supporting results with proper data and procedures.

In LCA models, uncertainty could be caused by three main causes: (i) data allocated to upstream and downstream processes, (ii) incorrect models, and (iii) incomplete models. Common practice is to represent uncertainty by a range or a standard deviation, which could be handled by Monte Carlo Simulation. Eco-invent database is constructed by two main data attributes as system processes and unit processes. Data uncertainty in unit processes is defined by a probability distribution recommended by the data collector.

In short, model uncertainties are originated from deficiencies in representing a real case. Environmental models have various design possibilities which are decided by the researcher. The researcher also determines type of data and data sources utilized in these environmental models. The important criteria for the data to be used are representativeness, allocation basis, and compatibility with products with long life

ranges. If data gaps are inevitable then the potential uncertainty will be handled by uncertainty analysis.

2.2 Historical Development of LCA

LCA studies started to be performed in early 1980's. Since then significant development and progress has been made by various researchers who could be called to be pioneers in the development of LCA. Some of these researchers studied industrial cases from the energy point of view. Boustead and Hancock (1982) studied energy requirements and recycling in steel production systems, tinplate production in the UK in the early 1980's pointing out the future of management and decision making in major industrial processes. Preparing detailed inventories of raw material and energy utilized during manufacturing processes can be considered as a predecessor of LCA.

Vigon and Jensen (1995) conducted surveys to document the range of variation in data quality in LCA practices related to data sources and databases. Finnveden and Östlund (1997) studied the applicability of using exergy as a measure of resources in the characterization of LCA. Exergy, defined as useful energy, was planned to be used for system boundary designation. This definition was considered to be remarkable as an improvement in characterization. Current trend observed in LCA studies is not based on entropy production or exergy as an indicator of resource consumption. New terms like exergy were defined all over world such as "ökobilanz" in Germany or "écobilan" in France, however, the sudden revival of LCA in all industrial sectors earned itself a more precise and powerful meaning with the analysis "from cradle-to-grave". Certain assumptions and exclusions, such as production losses, are drawbacks of the study (Finnveden and Östlund, 1997). However, fuel requirements for producing different materials from ore in the ground might be a useful data-set to be utilized in other research studies.

Klöpffer (1997) reviewed LCA while contributions of SETAC and shift of studies applying LCA were summarized. LCA methodology was criticized from beginning to current state pointing out the improvement in years. The author also stated that introduction of new characterization categories supported development of LCA.

After some life cycle inventories were introduced in every branch of industry, environmental burdens became an additional input in studies about industrial applications. Improvements in LCA concept were initiated by researchers as Assies (1998) and Vigon and Jensen (1995). Assies (1998) aimed to improve LCA by introducing risk terms to better harmonize methods in impact assessment.

Certain acceptance in international means for LCA was developed even though there were still uncertainties about the quality of data used. Peña (2002) summarized the general activity of LCA in Chile and introduced leading institutes in environmental research. SIMAPRO software was used for a copper cathode production case. Eco-indicator 99 was used as impact assessment methodology without any modification. For that study, unit processes and emissions related to the mining industry were not defined in detail, thus, some additional data were used throughout the analysis. Besides, predefined databases were utilized in case relevant measurements could not be taken on field.

Studies for national emission inventories inspired researchers. Jolliet *et al.* (2003) developed a new impact assessment methodology (IMPACT 2002+). Different impacts, such as marine environment and noise, were considered to be newly researched topics aided by available databases by the authors. Data availability and data quality are stated as basic components to be considered in LCA studies.

Improvement in the methodology of LCA and sub-categories, such as LCI, continued by contributions from researchers. Castells *et al.*, (2003) studied Monte Carlo Simulation for uncertainty assessment of a LCI for electricity generation from waste, Sonnemann *et al.* (2004) published a book called “Integrated Life-Cycle and

Risk Assessment for Industrial Processes". This publication gives basic information about LCA in accordance with ISO standards. Applications of LCA are explained by case studies from various fields.

Most countries started to build up their own life cycle inventory databases as it is observed from the study of Xianzheng *et al.* (2006) who studied research and development of Chinese LCA database and software. That study pointed out the governmental support in China for the evaluation of 42 kinds of metal and 58 nonmetal characterization factors. Data quality for any kind of collected data is an issue to be handled with care during the LCI stage.

2.3 LCA Applications in Industrial Fields

LCA gained importance and became more popular worldwide after the preparation of databases by governmental institutions in the USA, in the UK, and in EU countries. Turkey, as a geopolitically important country for both Europe and Middle East, also started to generate national environmental emissions database in an effort to represent the country. Elbir (1997) suggested a method for preparation of emission inventories in Turkey and provided some brief information about international projects, such as EUROTRAC/GENEMIS and OECD-MAP.

Özeler (2002) contributed to the national database by the LCA application in municipal solid waste treatment study. The functional unit of the study was the amount of solid waste generated in the system area of concern. Using site specific data and defining input/output for different scenarios, lowest contribution to GWP was calculated for the anaerobic digestion process. Although LCA is based on a location independent concept, Lenzen and Wachsmann (2004) studied the effect of geographical variability.

Since renewable energy sources such as biofuel, solar, and wind, compared to crude oil products has potential to reduce GHG emissions, Cleary *et al.* (2006) conducted a life cycle about the Canadian peat extraction for non-fuel purposes, such as horticulture. Cleary *et al.,* (2006) claimed that Kyoto's requirements about future of the environmental burden of Canada were stated to target a six percent reduction in 1990 levels between 2000 and 2008. Since peat extraction was stated to be a minor industry in former years, a reduction as stated in Kyoto Protocol seems to be unreachable for this case (Cleary *et al.*, 2006). Mining industry in Turkey will encounter similar problems due to the commitment made in Kyoto Protocol. In order to clarify the applicability of Kyoto requirements by means of emission reduction, estimations and models will be utilized for local cases prior to policy enforcements.

LCA studies conducted for industrial sectors are commonly based on local data which reduces the uncertainty and creates realistic representations. Site specific data, in case it is accessible, is advantageous in representation of industrial applications. Cordella *et al.* (2008) studied LCA of an Italian lager beer and defined their functional unit as one liter of beer and the fraction of packaging allocated to it. SIMAPRO software and Eco-indicator'99 method were used throughout the study. After comparing kegs and glass bottles, the authors concluded that kegs caused lower environment load. It was possible to point out that brewing process was not a critical stage using data directly gathered from the brewery. Therefore, the beer manufacturer might not be a crucial actor in the overall impact quantification. Determination of operations where it is obligatory for the company to make improvements by LCA may similarly be utilized in the mining industry. Comparison of equipment in the mining industry is a common topic in which environmental assets should be considered by the company.

In contrast to local data utilization in LCA studies, Eicker *et al.* (2010) investigated the applicability of non-local LCI data for LCA of triple superphosphate (TSP) production in Brazil. The authors compared three different datasets: European,

modified European, and Brazilian. Inaccurate results might be caused by nonlocal LCI data originated from spatial differences between the location of data gathered and location of the LCA study. As a result, the largest difference was observed for transportation caused by the portion of renewable energy used in Brazil. Environmental impacts found using Brazilian data were considerably low compared to European datasets as smaller number of inputs was in the scope of Brazilian data. Results of the study utilizing Brazilian data pointed out that local or in-site data might not always lead to accurate and realistic conclusions.

Although renewable energy sources such as bio-oil are considered to have less environmental impact, it is crucial to study transportation stage of such renewable energy sources by LCA. Kumar and Pootakham (2010) compared pipeline versus truck transport of bio-oil and emphasized that although that biomass yield is low per unit area its energy density is rather high. The authors built their model on an assumption of 100 km pipeline transportation through an insulated high density polyethylene corrosion resistant material. A plant having 400 dry tonnes per day capacity was used for comparison and the functional unit was defined as “per cubic meter of bio-oil per kilometer of transport”. As a result, the authors declared that truck transport was better than pipeline transport when the electricity for pumping was generated from coal. Source of power generation was stated to be the basic impact source which also pointed out the importance of investigating clean coal production.

2.4 LCA Application in Mining Industry

Although LCA is commonly utilized in various industrial fields, LCA in mining industry attracted a little attention. Reviewed studies indicate the potential of LCA as a supportive tool in decision making and management in minerals industry. Application of LCA in mining industry would support cleaner production of non-renewable energy sources.

Landfield and Karra (2000) evaluated a crusher in terms of energy consumption and environmental impacts over the life cycle of this equipment. Góralczyk and Kulczycka (2004) studied the financial aspects of LCA in Polish mining industry as an implementation of LCA in Europe. Non-measureable effects of LCA are stated as improved image and decreased competition for a company. The authors clarified the potentials of LCA as a tool that should be supported with a financial analysis.

In order to compare technically equivalent projects or equipment, inventories about material, energy inputs and emissions are prepared for various industrial fields. Babbitt and Lindner (2005) considered coal for electricity production in Florida and studied the inventory mainly in three stages: (i) coal mining, (ii) coal combustion, and (iii) treatment of coal combustion products. Data for each process was collected from interviews with authorities, surveys with managers, and the literature.

Durucan *et al.* (2006) developed a mining life cycle model and stated that data availability was a major concern in LCA as it might be highly confidential for mining companies. Representing mining operations at a high level of detail causes problems as there are sub-activities occurring at the same time with insufficient data for inputs and environmental burden. The database was based on a flexible object-relational code which allows modification and update of unit processes without disturbing overall model structure. However, highly confidential information is used during the development, such as a Bauxite mine in Hungary; however, certain data is not suitable for utilization in every project.

Another country that prepared its domestic LCA database and started to use this sustainable approach in mining industry is Mexico, a worldwide leader in silver production. Environmental management and life cycle approach in the Mexican mining industry was studied by Suppen *et al.* (2006). The authors indicated the role of this approach by stating the systematic observation of processes for potential impacts; reduce in operating cost and improvement in efficiency. Unavailability of statistical information in terms of production, industrial process for small- and

medium-scale companies reveals the need of choosing a large-scale operation as subject. Difficulties confronted during data collection for example publicly available data was a common problem in all studies reviewed.

LCA can be considered as a decision making tool on its own, together with expert knowledge and economic analysis it can also be utilized as a supportive criterion. Stewart and Petrie (2006) dealt with South African and Australian mineral industries in a comparative manner to point out the importance of life cycle inventories. The authors confronted certain difficulties in data availability and concluded that change-oriented LCA is a more valuable tool for decision making. Comparison of Australian and South African gold industries was based on input and output to the processes; however, technologies used are different from each other, thus major difference occurs in sulphur emissions and steam power or hydrogen consumption. Importance of applying the LCA methodology in a change-oriented mode in decision making was again stated and marked out that it was essential to prepare more generic models for mining industry with data availability problems.

Mining industry is equipment driven sector where decision making especially in this subject is commonly debated. Demirel *et al.* (2007) implemented a LCA comparison of mechanical and electrical drive trucks to identify stressor categories and air emissions of mine trucks in a medium scale mine in terms of GWP and acid rain precursors (ARP). The functional unit was defined as transporting 10,000 tph of coal from mine site to the processing plant using five km haul road, 1.3 km of which is in the form of ramps with eight percent slope. As a result of the study, the mechanical drive truck was more environmentally friendly in terms of GWP, although the contribution of electric drive trucks to the ARP were greater than that of mechanical drive trucks. For this reason, the authors also applied multi-criteria decision analysis techniques to develop a decision support tool for mine managers, mine owners, and environmental policy makers.

Use of LCA in the mining industry and research challenges was studied by Lesage *et al.* (2008) pointing out the two-fold relevance. The authors stated that mining industry has a role providing the LCA community with primary environmental impacts of materials such as metals. Furthermore, mining industry can use LCA in order to evaluate environmental impacts of its activities and identify their hotspots. The authors also studied an abandoned copper mine in Quebec, defining their functional unit as the management of the total production (1994-2005) of tailings from processing copper and zinc for the extraction of 15,500,000 tons of ore. It was stated that contrary to other impact assessment methods, such as Environmental Impact Assessment (EIA), LCA was developed as a space- and time-independent environmental assessment methodology. This might be correct for global categories, such as global warming or ozone depletion potential but might cause some erroneous results in regional categories, such as landuse.

Significant maintenance problems are encountered in the mining industry according to the high availability and reliability requirement of machinery and equipment. Equipment comparison both in capital investment stage and during operation should consider emissions. LCA approach is a practical way to indicate environmental load of machinery used especially in production. Barkhuizen and Pretorius (2008) conducted a survey on mining industry about the maintenance periods and the concept of predictive maintenance where parts are changed prior to fail. The cradle-to-grave approach was employed throughout the study to track down all emissions and environmental burdens of relevant machinery concluded as the development of reliable maintenance management.

There are recent studies of LCA in tailing management. Reid *et al.* (2009) used LCA for comparison of two possible scenarios: sending tailings to the disposal area where they are submerged or partly used as backfilling material. The authors stated that results of this study should certainly be supported with technical assessment of closure options, however, this study pointed out the lack of data for mining in LCA software and databases.

Critical reviews of LCA in the minerals and metals sector also point out the necessity of LCA studies in the mining industry. Yellishetty *et al.* (2009) summarized major events in LCA history and stated a recent discussion in mining industry. Although SETAC initiated two working groups in 1996 and 2002, no widely accepted methodology for landuse category is present. The authors also stated that spatial and temporal differentiation would greatly improve reliability and validity of LCA results. It was recommended that more time- and location-specific data needs to be utilized.

As there are difficulties and uncertainty in using databases to represent mining industry, it is usually impossible to take direct measurements to estimate GHG emission, especially CO_2. On-site measurement of CO_2 from fuel combustion is usually inapplicable because of its cost and labor intensity. Bogunovic and Kecojevic (2009) stated that substitute methods converting fuel or electricity consumption to fixed carbon contents and then to CO_2 emission is a more convenient way. Estimating GHG emissions and methodologies such as LCA are potential centers of attention as carbon taxes will enforce mining industry to become more environmental sensitive. As this method of emission calculation is based on energy or fuel consumption, data availability is substantially overcome.

Estimated GHG emissions are potential guidelines to determine critical stages of mining operations where improvement is required by utilizing spatial and case representative data. Lack of such data forces researches to make assumptions and exceptions. Norgate and Haque (2010) carried out LCA studies for mining and mineral processing of iron ore, bauxite and copper concentrate. Due to lack of publicly available data, mining and mineral processing stages were not considered in detail. SIMAPRO software was used to analyze three different cases. The authors stated that the largest contribution to total GHG emissions for mining and processing of iron ore and bauxite were made by loading and hauling. Approximately 87 percent of total energy consumed in materials handling are

accounted by diesel technologies and 50 percent of the GHG emissions are originated by the loading and hauling.

Another study LCA in metal industry was conducted by Eckelman (2010). The author considered GHG life cycle assessment of the global nickel industry. Eckelman (2010) determined the functional unit as one ton of nickel or nickel alloy and aimed to account for energy and GHG emissions, but not using average values. As a result, it was concluded that smelting and refining stages consumed the most energy and were responsible for the highest GHG emissions. Some drawbacks of the study were caused by the data that was not updated for production, trade, and energy. The only externally defined process with its upstream input was fuel production; however, there might be more environmentally considerable processes. Assumptions such as no material loss during transportation of nickel ore may also be reasons for uncertainty in the model.

A critical review of LCA applications in the mining industry was conducted Awuah-Offei and Adekpedjou (2011). The authors reviewed LCA studies and recommended that further researches in this field should be conducted. LCA has a potential to become commonly used in mining, especially equipment selection and this can only be aided by researches conducted in this field.

2.5 Critical Overview of LCA in Turkey

LCA can be considered as a niche research field in Turkey developing together with researches and applications in various industrial fields. Sözen *et al.* (2007) forecasted GHGs in Turkey based on sectoral energy consumption for Turkey. According to Sözen *et al.*, (2007), energy demand of Turkey has an increasing trend; however, GHG emissions are considerably below the average of EU countries. The authors stated that majority of energy production is based on coal, specifically lignite with a total share of 43 percent and also Kyoto Protocol has

major importance in limitation of GHG emissions and pointed out coal as one of the primary subjects to be studied in Turkey for environmental considerations.

Çakmaklı (2007) studied LCA of building materials that generate millions of tons of GHG, toxic air emissions, water pollutants, and solid wastes that contribute to negative environmental impacts. In this study, ATHENA software was used to evaluate three hotels in Ankara that were renovated according to the six environmental impact indicators: primary energy consumption, solid waste, air pollution index, water pollution index, GWP, and weighted resource use. As a result, the author recommended certain products to designers in order to lead more environmental friendly selections.

Recommendations to the packaging industry were made by Küçükgül and Doğan (2007) who evaluated LCA of poly ethylene terephthalate numerically with material-energy-waste-environmental impact circle. The authors utilized data from World Bank Group for emissions of crude oil production and they followed IPCC reference documents for other production stages. Basic emissions, such as CO_2, CH_4, and SO_2 were planned to be derived from the fuel consumption defined in IPCC guidelines, however, using a complete data-set was preferred in order to represent the case in a more accurate way.

Besides IPCC methodology for emissions, it is also possible to derive these from specific data reported in the subject area. Ertem and Akar (2008) studied a practical fossil fuel based CO_2 emission calculation methodology for industrial companies to monitor and control their environmental burdens. Steel industry was selected as research area and data was obtained with IPCC methodology. However, it was suggested that plants should report their own specific consumption data for more accurate assessment studies. Calculation methodologies, such as IPCC suggested mostly average values which in turn have to be adapted to specific fields.

Besides the limited number of researches, there is still no LCA regulation in Turkey for any industrial process or product. Turkey became signatory to the Kyoto Protocol and is obliged to develop strategies for emission reduction and cleaner production in every industry. LCA methodology was introduced to the industry by workshops and training programs for LCA software. Such events revealed the lack of primary data for every material and process in Turkey. Reviewed literature about the origin of LCA and applications in mining industry is summarized in Table 2.5.

Table 2.5 Summary of Literature Review about LCA

Year	Researchers	Location	Used Data and Details of the Research
2000	Landfield and Karra	-	Data about crushers, LCA of a commercial crusher
2002	Peña	Chile	Eco-invent, LCA of copper cathode production
2004	Lenzen and Wachsmann	Brazil	LCA of energy generation technologies,
2004	Góralczyk and Kulczycka	Poland	LCA of Polish mining industry
2005	Babbitt and Lindner	-	Interviews with authorities, surveys conducted to managers and the literature, LCA of electricity generation from coal
2006	Durucan *et al.*	Hungary	LCI generation
2006	Suppen *et al.*	Mexico	Mexican LCI database generation
2006	Stewart and Petrie	Africa and Australia	LCA comparison of African and Australian industries
2006	Xianzheng *et al.*	China	42 metal and 58 nonmetal characterization factors, Development of a national LCI database
2007	Demirel *et al.*	-	Data from SETAC and literature in Canada, LCA comparison of diesel and electric drive mining trucks
2008	Lesage *et al.*	Canada	Eco-invent, LCA of an abandoned mine
2009	Reid *et al.*	Canada	LCA comparison of tailing management
2009	Yellishetty	-	Data from literature, Review of LCA history
2009	Bogunovic and Kecojevic	-	Fuel consumption data, Conversion of fuel consumption to emissions
2010	Norgate and Haque	Australia	LCA comparison of iron ore, bauxite and copper concentrate
2010	Eckelmann	-	Data about global nickel industry, LCA of nickel industry
2010	Eicker *et al.*	Brazil	Comparison of different data-sets
2010	Kumar and Pootakham	-	Data about biofuel transportation, LCA comparison of trucks and pipelines
2011	Awuah-Offei and Adekpedjou	-	Review of LCA literature

2.6 Rationale of This Research Study

This study introduces LCA to the Turkish mining industry and evaluates environmental profiles of material handling systems with excessive amount of fuel consumption for an open pit coal mine. The main novelty of this study is that it is one of the first studies in applying LCA in the Turkish mining industry where considerable amount of emissions occur due to material handling. This study also advances the current knowledge about environmentally critical processes in material handling systems and places recommendations about both alternatives for better decision making. The results of the study are expected to provide a decision support system for mining industry.

Importance of this study is supported by the potential of LCA methodology as a decision support criterion integrated to mine management systems. Common utilization of LCA in mining industry is of paramount importance, as primary energy production depends on coal in Turkey. Mining industry will implement LCA and utilize environmental data in order to handle future considerations about environmental effects and related obligations.

CHAPTER 3

COMPARISON OF OFF-HIGHWAY TRUCKS AND BELT CONVEYORS IN AN OPEN PIT COAL MINE USING LIFE CYCLE ASSESSMENT

In this chapter, off-highway mining trucks and belt conveyors in an open pit coal mine are compared in terms of acidification and climate change using LCA. The conceptual study was started with an extensive literature survey about LCA and its applications in mining and other industries. Then, all publicly available data sources about environmental effects were reviewed. Off-highway mining trucks and belt conveyors were disintegrated into their unit processes to determine relevant upstream and downstream processes. The system boundaries for both material handling systems were determined according to the available data in SIMAPRO (Pre, 2011) software which was utilized for modeling. The system was divided into manufacture and utilization phases as separate assemblies to point out effect of energy consumption. The comparison results are interpreted according to acidification and climate change impact categories. These categories were selected as major concerns of the mining industry. Finally, uncertainty assessment was conducted with SIMAPRO using Monte Carlo Simulation tool.

In this chapter, conceptual modeling in LCA comparison of off-highway trucks and belt conveyors is presented in detail. Unit function and system boundaries are identified in goal and scope definition stage. Gathered and modified data utilized in LCI generation is specified in this chapter. Acidification and climate change impact categories are defined and information about the interpretation of the conceptual LCA comparison is presented. Simulations are conducted in SIMAPRO software. The uncertainty analysis carried out using Monte Carlo Simulation is presented in this chapter.

3.1 Conceptual Modelling of LCA Comparison of Off-highway Trucks and Belt Conveyors

Conceptual modelling of LCA comparison of off-highway trucks and belt conveyors followed the methodology as summarized in the flow diagram given in Figure 3.1.

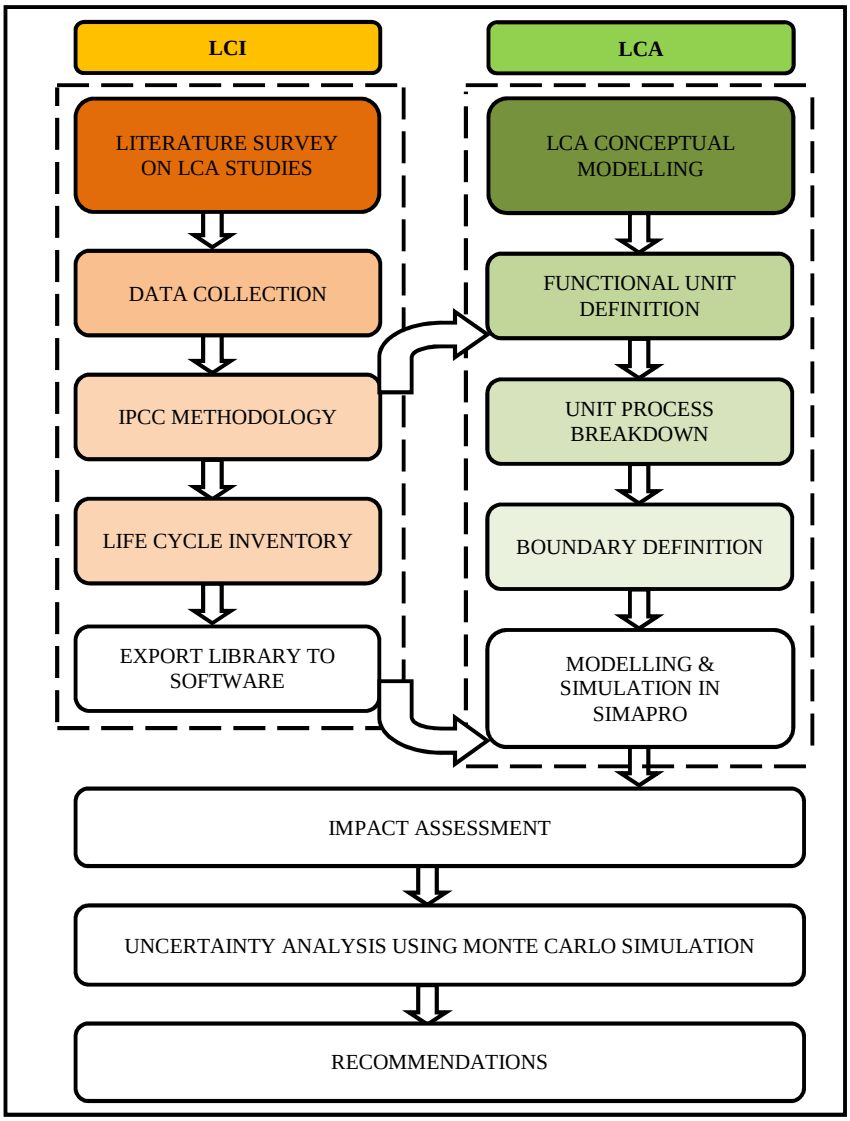


Figure 3.1 Research Framework

Literature survey about LCA applications in mining industry and review of publicly available data proceeded with unit function definition. Both material handling systems were decomposed into their unit processes to determine upstream and downstream processes. Prior to modeling in SIMAPRO, boundary between the system and environment was selected. Results were evaluated according to acidification and climate change categories. Monte Carlo simulation was applied in SIMAPRO for uncertainty assessment.

Review of publicly available data indicated that Turkey as a developing country (OECD, 2009) generates its primary energy from fossil fuels. Gross Domestic Product (GDP), economic growth rate and energy consumption of Turkey is foreseen to increase until fossil fuels will be used up. Increase in growth rate is declared by the TSI as 12.7 percent in 2008, whereas, exports were recorded as $73.4 billion with an increase of 2.6 times compared to 2000 (TSI, 2008). Energy consumption is also rated as a key indicator of development and 3.7 percent increase stated by TSI proves the energy demand. Energy is considered to be the primary GHG emission source in Turkey.

Waste disposal and industrial activities are other primary GHG emission sources. Conversion of energy to electricity is the main reason of the considerable amount of GHG emissions in energy sector. LCA studies about mining industry as a part of the energy sector require foreground data. Therefore, accessible data sources were reviewed in detail to overcome data availability problem.

TKI is a major data source for coal mining activities that was utilized for primary data generation in the conceptual modeling. Figure 3.2 shows the distribution of equipment utilized in TKI's open pit mines and indicates that trucks have major importance in operation. Number of trucks utilized in open pit operations is 478 that is more than the total of other commonly used equipment such as dozers, loaders, graders, and excavators.

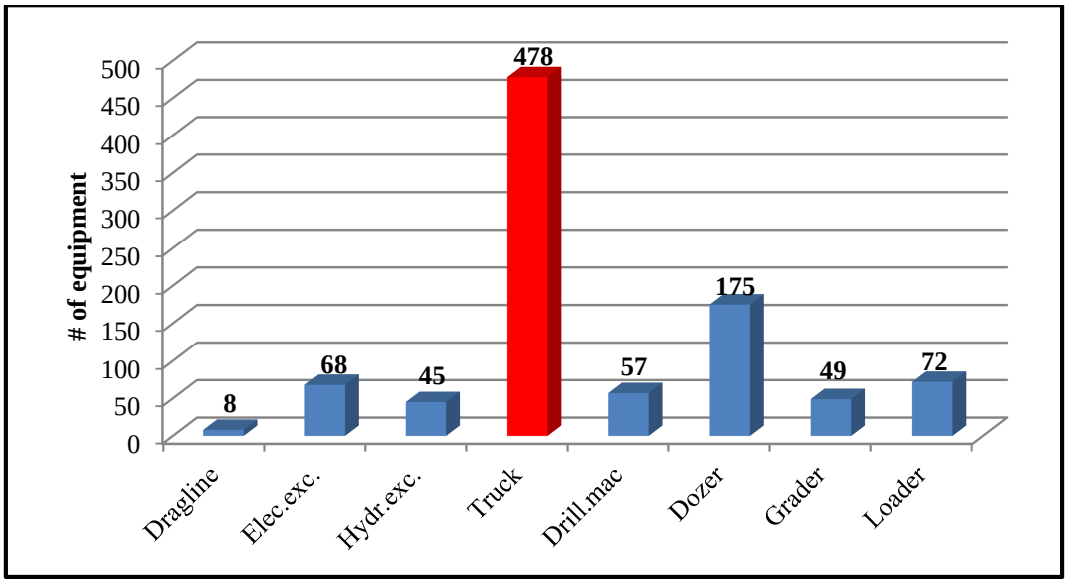


Figure 3.2 Number of equipment in TKI operations (2008)

Age of equipment utilized in open pit operations could be considered as critical. As it is illustrated in Figure 3.3, 20-25 years aged trucks are still commonly used in governmental open pit operations in Turkey. Majority of trucks with critical age are utilized intensively in open pit operations for material handling.

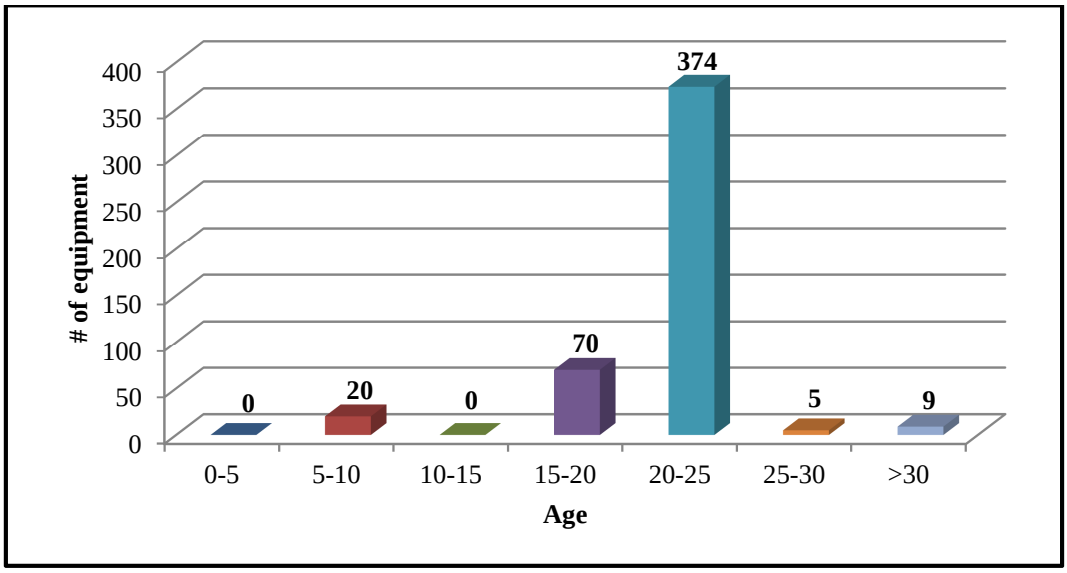


Figure 3.3 Age of trucks in TKI operations

OECD countries aim to reduce their emissions in national scale to a reference level set to 1990 and are obliged to support other member countries financially. Turkey started to prepare annual emission reports using the methodology defined by the IPCC, which was also used in the conceptual part to review surface operations of TKI. According to the IPCC, the most important greenhouse gases are stated to be carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluoro carbons (HFCs), perfluoro carbons (PFCs), and sulfurhexa fluoride (SF_6). Today's atmosphere contains only 0.038% CO_2. However, it is estimated that CO_2 is responsible for about 60% of the greenhouse effect attributed to the increased atmospheric concentrations of greenhouse gases.

IPCC methodology was used to estimate CO_2 emission of TKI open pit coal mines. As seen in Figure 3.4, Ege Lignite Enterprise (ELI) is the most critical operation among TKI coal mines also having the largest truck inventory. The details of data are presented in Appendix-B (Table B.1).

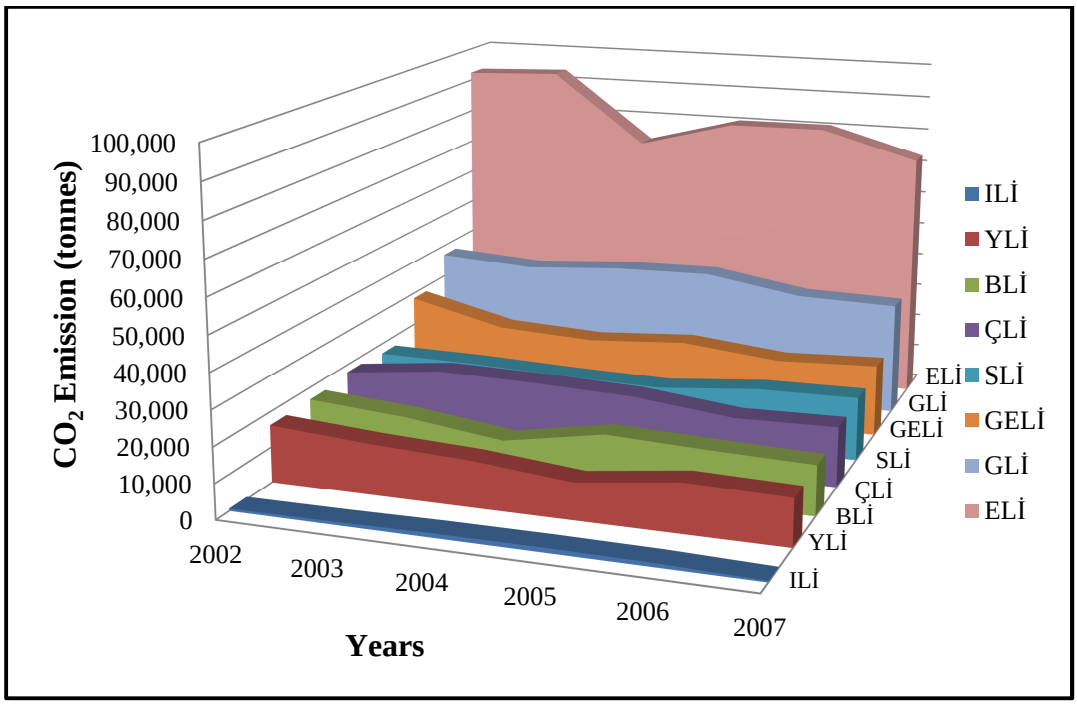


Figure 3.4 CO_2 emission of TKI open pit mines

Garp Lignite Enterprise (GLI) and Güney Ege Lignite Enterprise (GELI) operations emitted approximately 30,000 tons and 20,000 tons of CO_2 respectively according to their fuel consumption in 2007. Emitted CO_2 amount could be considered as directly proportional to the amount of production and fuel consumption of trucks.

The decrease in CO_2 emissions as it seen in Figure 3.5 can be aided by the conducted LCA comparison. Results of the comparison clarified if there is a more environmentally sensitive way of haulage and if improvement is required in certain stages of the operation.

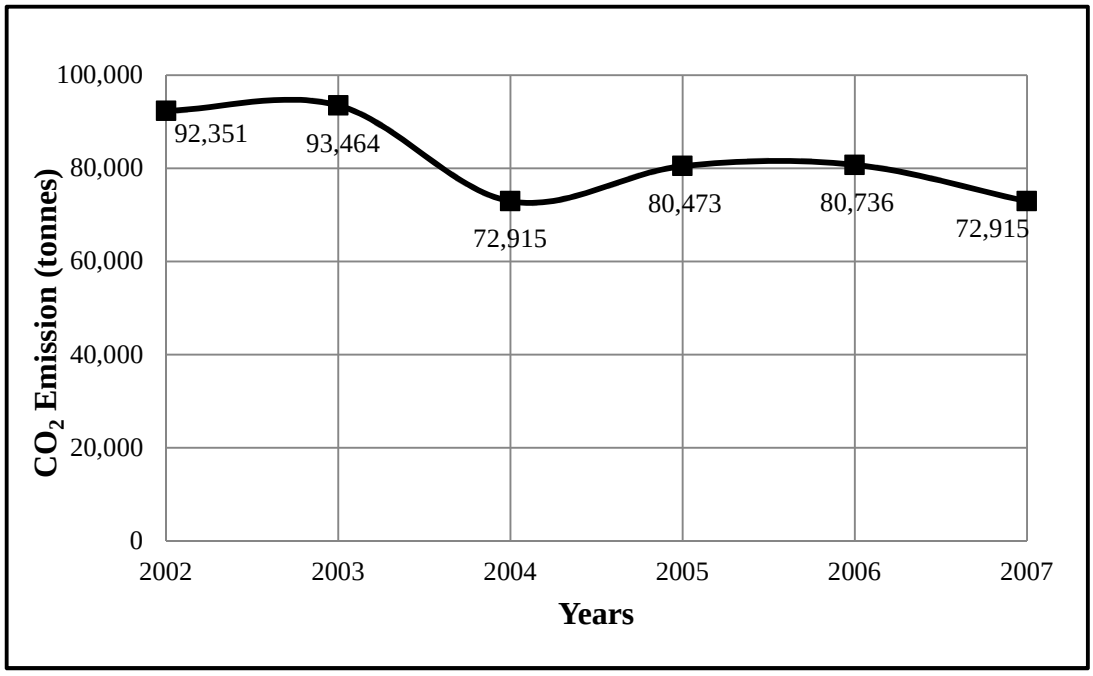


Figure 3.5 CO_2 emission of Ege Lignite Operation (ELI)

Decrease of emissions in ELI could be related to the equipment renewal periods as it can be observed in 2004. As a result of the conceptual study, environmental load of the truck haulage in TKI operations was determined. Only CO_2 emissions were estimated in the conceptual LCA comparison of off-highway trucks and belt conveyors.

3.1.1 Goal and Scope Definition of the Conceptual LCA Model

Goals of the conceptual model are: (i) gathering data for off-highway trucks and belt conveyors in an open pit coal mine, (ii) constructing an inventory about environmental effects, (iii) comparing both material handling systems according to their impact in acidification and climate change, (iv) conducting an uncertainty assessment, and (v) suggesting improvement in critical stages. Scope of the study covers all life cycle stages for both off-highway trucks and belt conveyors except their recycling and waste management.

Unit Function Definition: In order to compare the mining trucks and belt conveyors on a technically equivalent basis, a conceptual production amount was estimated from several open pit operation's average as 20,000 tons/day. It was computed that for an optimized shovel-truck system, 80 tons of coal with bulk density of 0.89 tons/m^3 is loaded with a 15 m^3 capacity shovel with a fill factor of 0.8. Coal handling will be performed on a five km long, well-maintained road. The haulage road is designed to be covered with gravel and following properties summarized in Table 3.1 are estimated from previous studies in the literature. Coefficient of friction for dry and wet conditions was taken as 0.6 and 0.4 respectively. (Karpuz *et al.*, 2005) Grade resistance and rolling resistance of the haulage road were used as five percent and three percent respectively.

Table 3.1 Haulage road properties

Parameter	Value
Coefficient of friction (dry)	0.6
Coefficient of friction (wet)	0.4
Grade resistance	5%
Rolling resistance	3%

Most of the equipment used in haulage operations is old. This causes difficulties data gathering. For this reason, an off-highway truck classified as medium impact steel flat floor with properties presented in Table 3.2 was selected as technical data was readily available.

Table 3.2 Properties of selected off-highway truck

Property	Value
Target Payload	46,236 kg
Struck Capacity	23.3 m^3
Heap Capacity	31.3 m^3

CAT 772 off-highway truck was initially selected with regard to its capacity and bulk density of the material. As it can be seen in Table 3.2, struck and heap capacity of the truck is in accordance with the calculated material volume. Approximate bulk volume of 20 tons of lignite is 30.8 m^3 when similar trucks in TKI operations are considered.

Another important aspect in estimating total required number of trucks in an operation is the cycle time consisting of truck load time, spot time at shovel, haulage time, maneuvering - dumping time, and return time. In case loaded truck is considered to be travelling against eight percent total resistance and empty truck is travelling against two percent resistance where five percent favorable grade is present, total cycle time is calculated as 24.5 minutes. Haulage and return time were estimated from Figure 3.6, whereas load time, spot time, and dumping time were assumed based on literature and used for total cycle time calculation for optimum conditions.

The truck manufacturer prepared charts of all vehicles for travel time estimation. It is stated that the vehicle is operated under normal conditions by average rimpull and

breaking performance (CAT, 2010). It is also indicated that loading is performed by a full bucket of a selected loading unit.

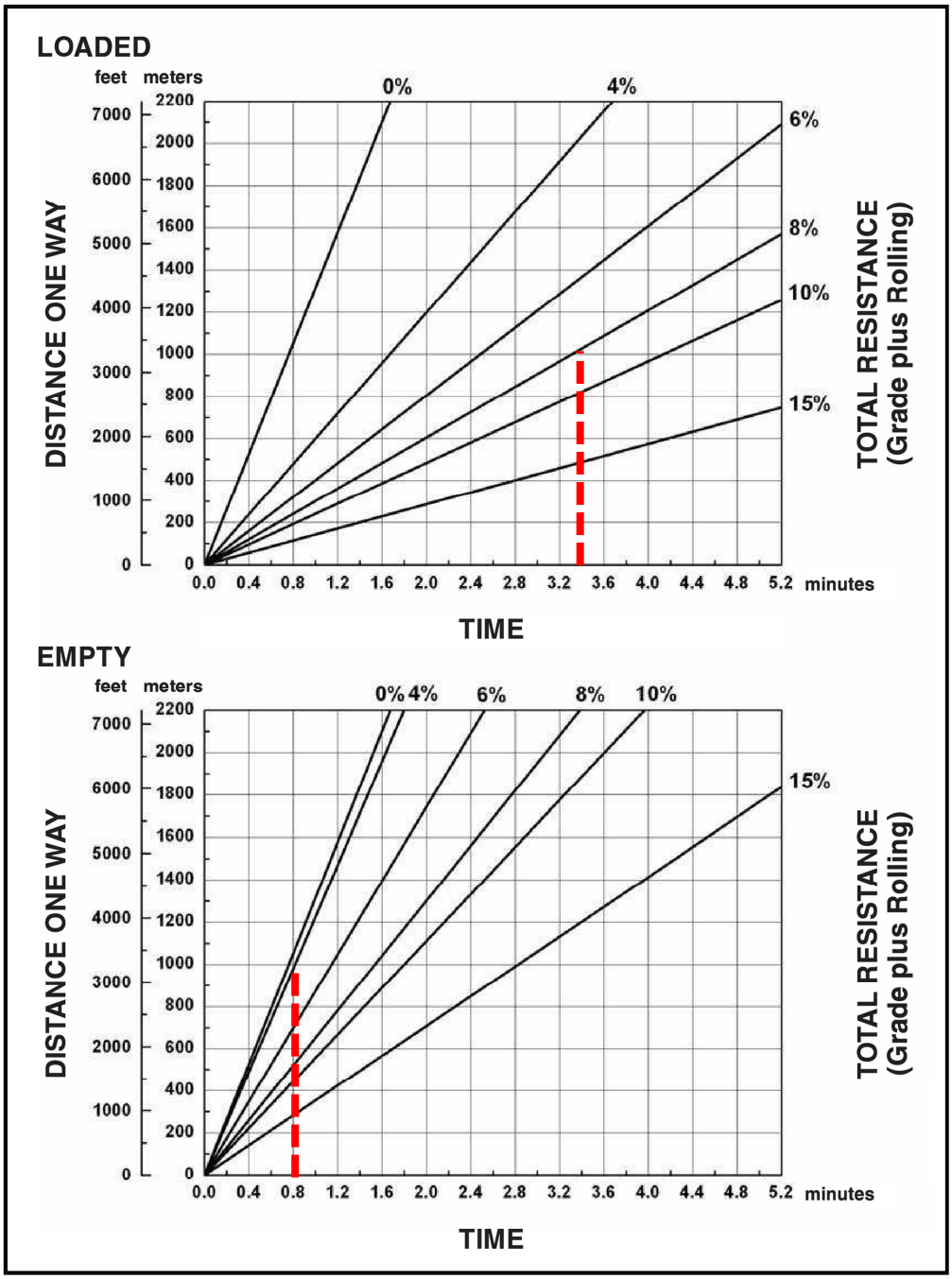


Figure 3.6 Performance charts of CAT 772 (CAT, 2010)

In order to compare off-highway trucks and belt conveyor systems on a technically equivalent basis, modifications were made according to a pre-determined production. An average production was estimated from TKI operations ELI, Seyitömer Lignite Enterprise (SLI), and GELI where trucks are used intensively as 20,000 tons/day.

Total required number of trucks was found using production capacity, cycle time, availability, and utilization. Availability and utilization were estimated by considering possible breakdowns and efficient operating hours as in case for an operation with the plan listed in Table 3.3.

Table 3.3 Mine Operating Schedule

Process	Duration	
Calender year operating hours (COH)	**7920 hours**	
minus major repair (overhaul) hours (MOH)		288 hours
minus statutory holiday hours (SSH)		360 hours
minus severe weather delay hours (SWOH)		72 hours
Scheduled Operating hours (SOH)	**7200 hours**	
minus Preventive maintenance hours (PMH)		104 hours
minus Breakdown Maintenance hours		336 hours
Mechanically Available hours (MAH)	**6760 hours**	
minus Operating delay hours (ODH)		1440 hours
Mechanically Utilized hours (MUH)	**5320 hours**	

According to Eqn. 3.1 and 3.2 (Karpuz *et al.*, 2005), availability and utilization were calculated as 93.8 percent and 78.7 percent respectively.

Availability (A) = $MAH/SOH = 6760/7200 = 93.8\%$ (Eqn 3. 1)

Utilization (U) = $MUH/MAH = 5320/6760 = 78.7\%$ (Eqn 3. 2)

As a result, availability and utilization values were classified as good job conditions and good management. Consequently, total number of required trucks for 20,000 tons/day capacity was found to be 23.

The belt conveyor to be used in the comparison study was selected by following the handbook published by the Conveyor Equipment Manufacturers Association (CEMA, 1997). Bulk density is the only key property of the material in truck selection; however, the other characteristics have to be known for belt conveyor design. Bulk density of lignite was considered as 0.65 t/m^3 (Gentry and Hustrulid, 1992). Angle of repose and angle of surcharge of lignite were taken as 38° and 25° respectively considering lignite as an average flowing material (CEMA, 1997). Further classification of lignite was carried out as it can be seen in Table 3.4.

Table 3.4 Material classification for lignite, D36T (CEMA, 1997)

Coal (lignite, D36T)

Property	Value
Lumpy, containing lumps over 1.5 cm	D
Average flowing	3
Abrasive	6
Mildly corrosive	T
Recommended maximum inclination	22°
Troughing angle	20°

According to determined material properties for lignite, belt speed was estimated as 3.56 m/s (700 fpm) as seen in Table 3.5. As a result, a single belt conveyor system with eight components is required for the production capacity of 20,000 tons/day.

Total power required to convey material from five km long haulage path was calculated to be 1,320 horsepower for the whole belt conveyor system by utilizing power rating charts (CEMA, 1997).

Table 3.5 Recommended maximum belt speeds (CEMA, 1997)

Material Being Conveyed	**Belt Speeds (fpm)**	**Belt Width (inches)**
Grain or other free-flowing, nonabrasive material	500 700 800 1000	18 24-30 36-42 48-96
Coal, damp clay, soft ores, overburden and earth, fine-crushed stone	400 600 800 1000	18 24-36 42-60 72-95
Heavy, hard, sharp-edged ore, coarse-crushed stone	350 500 600	18 24-38 Over 36
Foundry sand, prepared or damp; shake out sand with small cores, with or without small casting (not hot enough to harm belting)	350	Any Width
Prepared foundry sand and similar damp (or dry abrasive) materials discharged from belt by rubber-edged plows	250	Any Width
Nonabrasive materials discharged from belt by means of plows	200, except for wood pulp, where 300 to 400 is preferable	Any Width
Feeder belts, flat or troughed, for feeding fine, nonabrasive, or mildly abrasive materials from hoppers and bins	50 to 100	Any Width

Belt speed is determined by the material characteristics. Abrasive and heavy material is conveyed with lower belt speed when compared to soft and fine crushed material. Though, conditions how the material is fed on the belt conveyor also affects belt speed.

After belt speed was determined, required belt width was selected as 1.02 m (40 in.) according to a capacity of 20,000 tons/day. In order to estimate cross-sectional dimensions of the belt conveyor as seen in Figure 3.7, other parts were selected in accordance with the width of the belt.

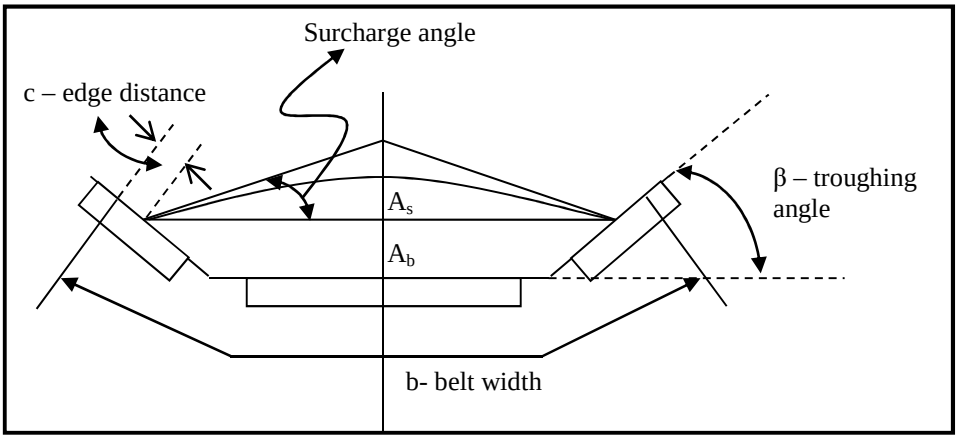


Figure 3.7 Cross-section of a belt conveyor (CEMA, 1997)

In order to determine power requirement of the belt conveyor system, idler type was selected and actual load was calculated. Power required for the belt conveyor system was calculated in detail utilizing power rating charts for empty belts, vertical, and horizontal haulage given in Table C.1, Table C.2, and Table C.3. As a conclusion, total power required to convey material from 5 km long haulage path is calculated as 1,320 HP for the belt conveyor system. In order to maintain efficient material haulage and prevent any sagging in the belt, tensioning devices were designed to provide required tension throughout the system. Theoretically, sagging greater than three percent will cause material spillage, accordingly so that minimum required tension is calculated as 435 kg.

Boundary Definiton of Conceptual LCA Comparison: System boundaries were planned to be selected utilizing RMEE methodology (Raynolds *et al.*, 2000) at the beginning of the study. Due to lack of primary data, Eco-invent database was utilized. Both material handling systems were disintegrated into their unit processes

as presented in Figure 3.8 and Figure 3.9 in order to review data availability and system boundaries. After review of publicly available data sources, it was preferred to use a complete data-set and make certain modifications. Therefore, system boundaries were implemented from the Eco-invent database where detailed background information was present.

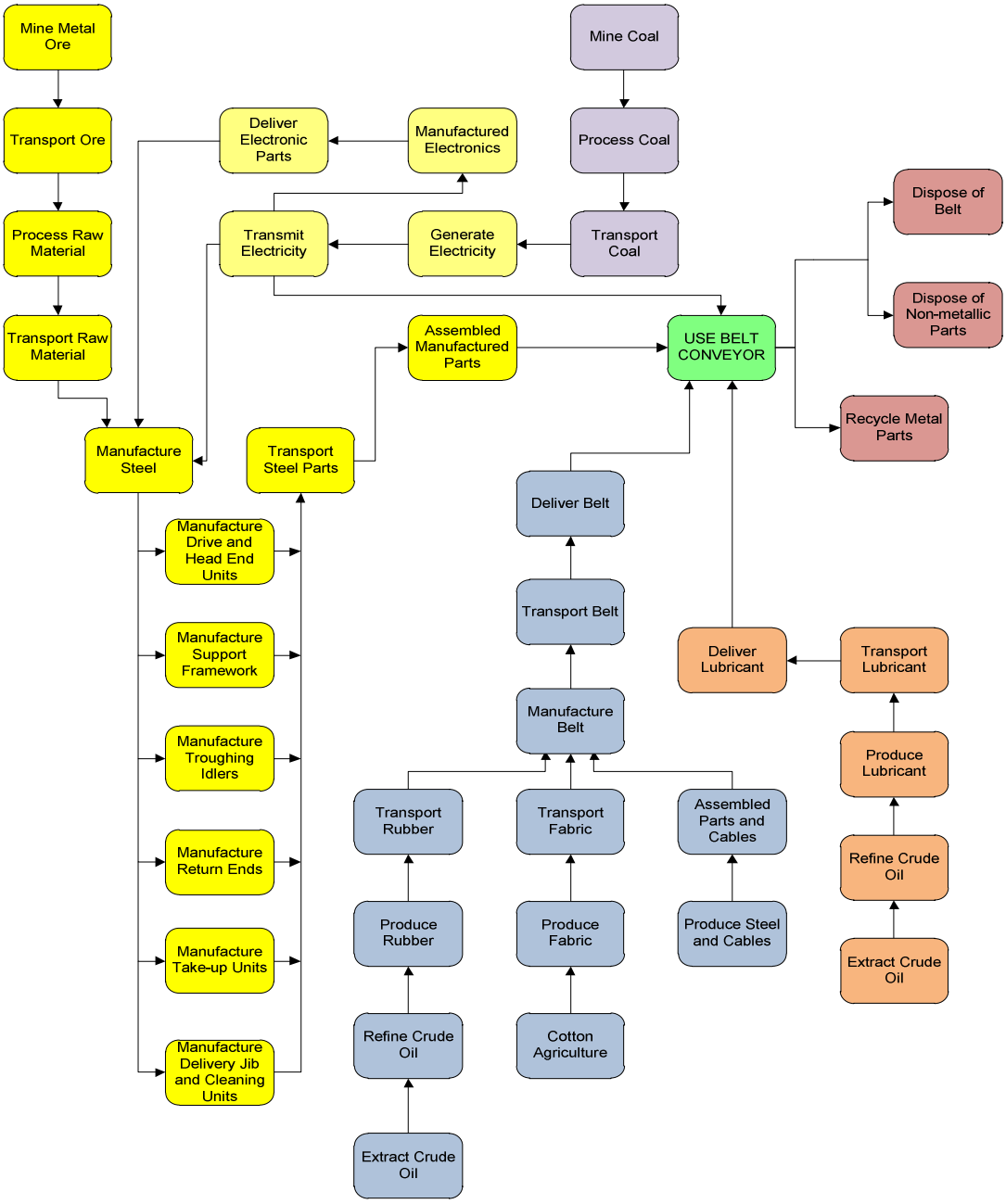


Figure 3.8 Unit processes of belt conveyor

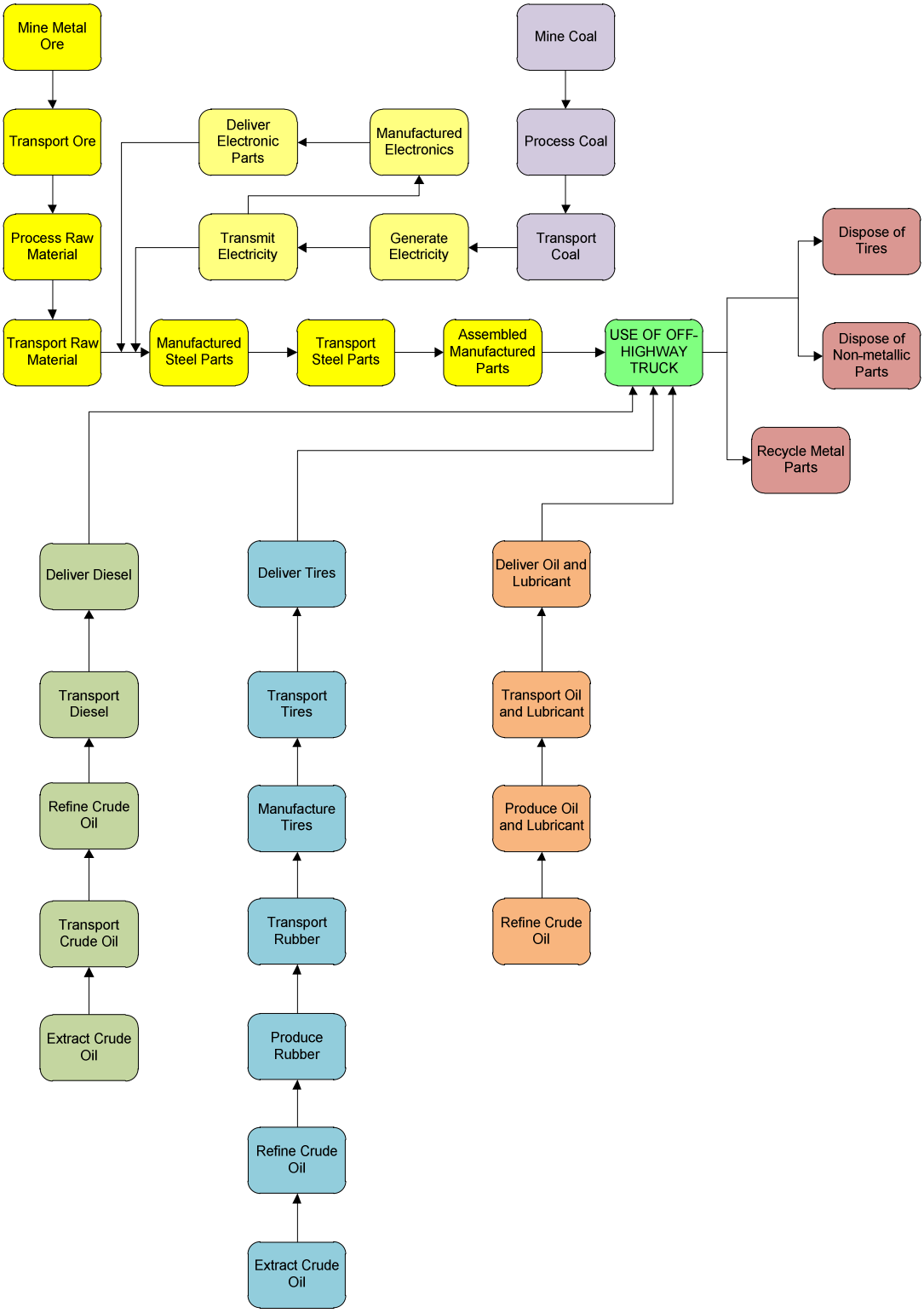


Figure 3.9 Unit processes of off-highway truck

Disintegration of both material handling systems made it possible to consider total life cycle of processes by summarizing background information. Besides, LCI stage was based on these unit process maps.

3.1.2 Life Cycle Inventory (LCI) of the Developed LCA Model

Available data from governmental institutions and literature were reviewed, however, it was concluded that scaling down datasets prepared for a country to a single mining operation would increase uncertainty. Data to represent upstream and downstream processes of both material handling systems was selected from Eco-invent database embedded in SIMAPRO and modified according to the information gathered from truck manufacturers and equipment suppliers.

Eco-indicator 99 version 2.08 was utilized as a primary data source. Eco-invent database was used with some modifications due to two main reasons. First, as many researchers claimed Eco-invent database provides a general outlook on the importance of transportation in a product's life cycle and environmental load heavily depends on vehicle sizes especially for road transportation (Spielmann and Scholz, 2005; Facanha and Horvath, 2006). Second, the lack of archive data for Turkey limit the study and it was considered that using a whole data-set is more reliable than using inaccurate and imprecise data for a particular spatial region, Turkey.

Operation of road vehicles is defined in Eco-invent by a common unit namely, ton-kilometer (tkm) defined as transport of one ton over one kilometer, or one kg over 1000 km, or any other combination that has the same product of distance and weight. As off-highway mining trucks are not described definitely in Eco-invent database, operation of a high capacity lorry was modified to reach a more realistic model. Fuel consumption was adjusted so that the selected process represents an off-highway mining truck with higher fuel consumption.

Electricity consumption of the belt conveyor was first evaluated for Bulgaria, Estonia, Romania, Poland and Slovenia as East European countries were considered to have similar electricity generation to Turkey. However, European Network of Transmission System Operators for Electricity (Entsoe) record formerly known as Union for the Co-ordination of Production and Transmission of Electricity (UCTE) was selected to represent Turkey. This average European data is classified into sub categories of country mixes and various voltages. As there is no background data for Turkey's electricity generation, electricity consumption of belt conveyor was represented by Entsoe as Turkey initiated its integration to this system in 2009.

3.1.3 Impact Assessment of the Developed LCA Model

Impact assessment for both material handling systems were conducted using SIMAPRO 7.3 software (Pre, 2011). Mining industry is energy intensive so that excessive diesel oil and electricity consumption results in emissions dominated by CO_2 and SO_x. Impact categories were selected as acidification, climate change to represent environmental load of material handling in the mining industry. The reason for choosing acidification and climate change is the fact that these two categories are more commonly used and discussed in minerals industry. Therefore, they might be used as basic environmental criteria during equipment selection. These categories can be considered as major concerns related to fuel and electricity utilization in surface mining. Leading mining companies initiated corporate sustainability reports such as BHP Billiton (2010) and Rio Tinto (2006) that support reduction measures for GHG emissions and pointed out the importance of acidification and climate change impacts in their operations.

Wide range of impacts on soil, groundwater, surface water, organisms, ecosystems, and materials (buildings) by acidifying substances was stated in the SIMAPRO database manual (Goedkoop *et al.*, 2008). Acidification can be defined as damage to ecosystem quality, as a result of emission of acidifying substances to air. Damage is expressed in Potentially Disappeared Fraction (PDF) x m^2 x year/kg emission.

Major source for this category is operation stage of the trucks combusting diesel oil and emitting ammonia (NH_3), NO_3, NO_x, SO_4, SO_2, and SO_3. Climate change can result in adverse effects upon ecosystem health, human health, and material welfare. This impact category is related to emissions of greenhouse gases, water vapor, CO_2, CH_4, NO_2, ozone (O_3), and chlorofluorocarbons (CFC). Damage is expressed in Disability Adjusted Life Years (DALY) per kg emission, resulting from an increase of diseases and death caused by the climate change. Other impact categories are summarized in Table 3.6.

Table 3.6 Eco-Indicator impact categories

		Description	Unit
Human Health	**Carcinogenic substances**	emissions of carcinogenic substances to air, water, and soil	Disability Adjusted Life Years (DALY) / kg emission
	Respiratory organics	resulting from summer smog, due to emissions of organic substances to air, causing respiratory effects	Disability Adjusted Life Years (DALY) / kg emission
	Respiratory inorganics	effects resulting from winter smog caused by emissions of dust, sulphur,, and nitrogen oxides to air	Disability Adjusted Life Years (DALY) / kg emission
	Climate change	resulting from an increase of diseases and death caused by climate change, (CO_2, CH_4, N_2O emission).	Disability Adjusted Life Years (DALY) / kg emission
	Ionising radiation	resulting from radioactive radiation	Disability Adjusted Life Years (DALY) / kg emission
	Ozone layer depletion	due to increased UV radiation as a result of emission of ozone depleting substances to air	Disability Adjusted Life Years (DALY) / kg emission
Ecosystem Quality	**Ecotoxicity**	result of emission of ecotoxic substances to air, water, and soil	Potentially Affected Fraction (PAF)*m^2*year/kg emission
	Acidification	result of emission of acidifying substances to air	Potentially Disappeared Fraction (PDF)*m^2*year/kg emission. (SO_X, NO_X, NH_3)
	Land-use	result of either conversion of land or occupation of land	Potentially Disappeared Fraction (PDF)*m^2*year/m^2 or m^2a
Resources	**Minerals**	Surplus energy per kg mineral or ore, as a result of decreasing ore grades	MJ
	Fossil fuels	Surplus energy per extracted MJ, kg or m^3 fossil fuel, as a result of lower quality resources	MJ

3.1.4 Interpretation of Conceptual LCA Comparison Modelling

Results of the conceptual model were represented utilizing the SIMAPRO interfaces. Comparison of off-highway trucks and belt conveyors according to climate change and acidification categories are presented in Chapter 4. Results in other impact categories are given in Appendix-D. Model uncertainties are evaluated by uncertainty assessment in SIMAPRO by utilizing Monte Carlo Simulation tool. Recommendations and critical review of the comparison of off-highway trucks and belt conveyors are given in Chapter 5.

3.2 Computational Simulation of Conceptual LCA Comparison Study

The conceptual study was modelled and computed in the SIMAPRO software. The SIMAPRO software is a professional tool to model products and systems from a life cycle perspective. SIMAPRO is fully integrated with the Eco-invent database and has additional features such as parameters and Monte Carlo Simulation for uncertainty assessment. Main application areas are carbon footprint calculation, product design and eco-design, Environmental Product Declarations (EPD), and environmental reporting.

First stage of computational simulation was to determine the level of detail for off-highway truck and belt conveyor models. In order to represent the dominant impact of fuel and energy consumption, utilization of both material handling systems were modeled separately in their life cycles. There is no specific data for the manufacturing process of off-highway trucks or belt conveyors. Certain estimations were made according to the information gathered from equipment manufacturers for amount of material used during manufacturing. As it is presented for the belt conveyor in Figure 3.10, both material handling systems were modelled as life cycles in SIMAPRO.

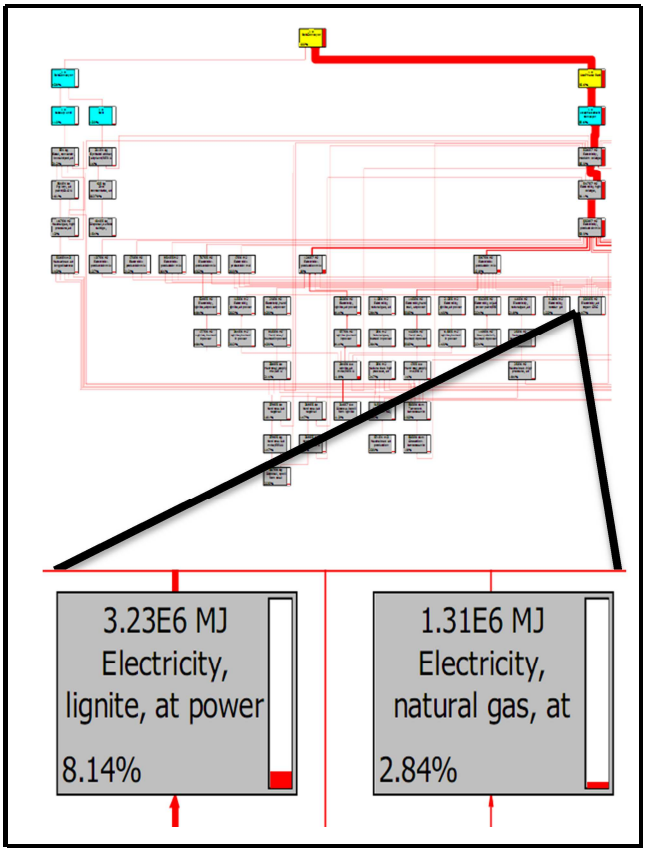


Figure 3.10 Life cycle model of belt conveyor in SIMAPRO

Off-highway trucks were modelled as an assembly consisting of steel parts, plastic parts and tires. O. Mezreli from Borusan Makina (e-mail, May 10, 2010) suggested that 85 percent of the gross machine weight could be considered as steel and 15 percent as plastic and tires manufactured from synthetic rubber. Steel and rubber were selected as primary raw materials for the off-highway truck from Eco-invent database. Selected steel data include background data about the transportation of scrap metal, steel making, and casting. Synthetic rubber process consists of crude oil transportation, production, and vulcanization of production profiles. Modelled off-highway truck is presented in Appendix-E (Figure E.1) as a detailed network.

Belt conveyors were categorized into steel parts as idlers, take up unit, support framework, return end, drive units, and cleaning unit. Amount of steel required for manufacturing of these parts were estimated from technical drawings of a belt

conveyor system in an open pit coal mine. Other main part modelled was the belt mainly composed of synthetic rubber. Detailed network of the modelled belt conveyor is given in Appendix-E (Figure E.2).

Utilization of off-highway trucks and belt conveyors were modelled separate from their manufacture process in order to point out the impact of diesel oil and electricity consumption. Diesel oil consumption of the off-highway truck was represented by a modified transportation process in the Eco-invent database. Modifications were based on calculated cycle times, availability, utilization, and fuel consumption data from truck manufacturer. Electricity utilization of belt conveyors was represented by an average data of UCTE from the Eco-invent database after process contributions of Eastern European countries were evaluated according to their process contribution as represented in Appendix-F. It was preferred to utilize UCTE data as an EU average as electricity generation data defined for Bulgaria, Estonia, Romania, Poland, and Slovenia were also not similar to Turkey. Electricity input was determined by the power rating of the belt conveyor.

3.3 Uncertainty Analysis for the Developed LCA

The inherent uncertainty in the conceptual model was assessed by uncertainty assessment conducted in SIMAPRO by the Monte Carlo Simulation tool. It is based on numerical integration and commonly utilized in probability problems. Definitions of Jacob Bernoulli are considered to be the origin of Monte Carlo Simulation (Dunn and Shultis, 2009). Simulation techniques are preferred instead of complex numerical integrations in problems with no analytical solution.

Uncertainty assessment of the conceptual study for off-highway trucks and belt conveyors was conducted in SIMAPRO. This analysis was carried out for acidification, climate change, and emissions of CO_2, NO_x, SO_x, and CH_4.

Uncertainty data as statistical distributions was prepared by specialists who gathered the data-sets for Eco-invent database. A total of 68,501 processes were utilized in the LCA comparison of the conceptual study. 72.1 percent of the utilized data is defined with a lognormal distribution. The reason of the dominance of lognormal distribution is that steel and other metal related data is commonly defined by lognormal distribution. As Eco-invent was utilized as the primary data source, it was not preferred to modify this data-set with user defined uncertainty distributions. Monte Carlo Simulation was conducted with different stop criteria as 100, 1000, 2000, 5000, and 10,000 in order to determine the sufficient amount of steps to reach stable condition. Different representations for mean, median, coefficient of variation, standard deviation, and standard error of mean are given in Appendix-G. 10,000 steps were considered to be sufficient for the system to reach a stable condition. Total computation time of 10 hours was spent to complete the Monte Carlo Simulation with a stop criterion of 10,000 steps.

CHAPTER 4

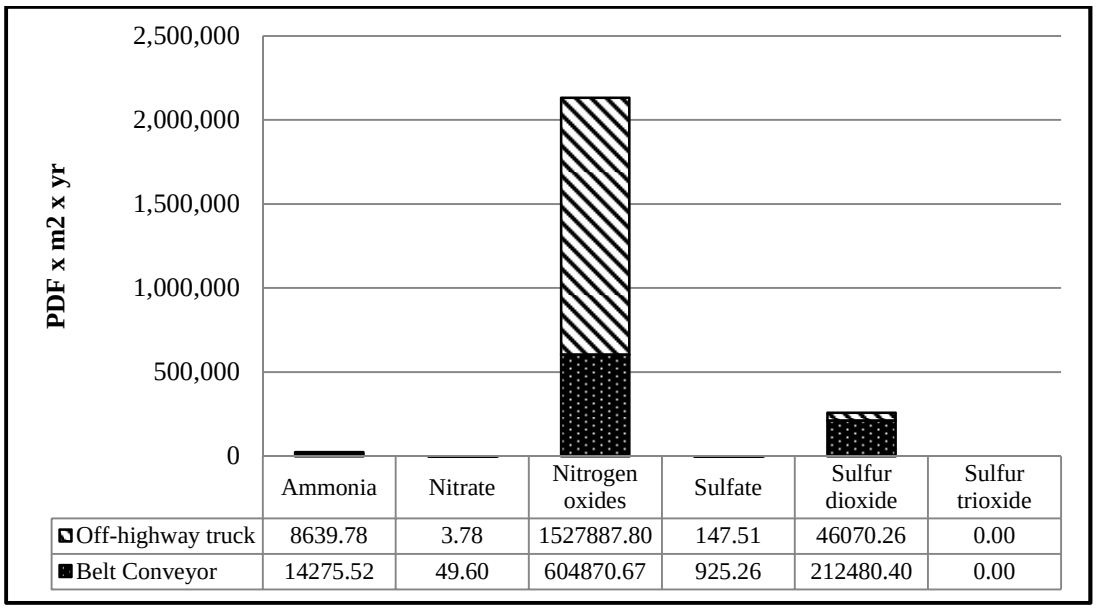
RESULTS AND DISCUSSIONS

In this chapter, results of the LCA comparison of off-highway trucks and belt conveyors are presented. Conceptual modeling in SIMAPRO is concluded and comparison results in acidification and climate change impact categories are described in detail. Besides, process contributions of processes in acidification and climate change categories for off-highway trucks and belt conveyors are stated. Uncertainty analysis is conducted by utilizing Monte Carlo Simulation for comparison results in acidification and climate change categories.

4.1 Results of LCA Comparison for Acidification and Climate Change

Analysis conducted by SIMAPRO software cover all impact categories defined in Eco-Indicator database. Climate change and acidification are selected as major impact categories. Although manufacturing stage had a significant impact on all of the environmental parameters, utilization stage was the hotspot for selected impact categories. The results of this study revealed that belt conveyors had greater environmental burden in climate change impact category when compared to the trucks. On the other hand, trucks have greater environmental burden in acidification impact category when compared to belt conveyors. The obtained results also indicated that the highest impact on all selected impact categories are generated from the utilization stage of the trucks operated by diesel oil and utilization of belt conveyor systems operated by electricity commonly produced by coal.

After modeling the off-highway trucks and belt conveyors in SIMAPRO, major environmental loads and process contributions of the systems were determined for all impact categories and focused on acidification and climate change. Acidification impacts of off-highway trucks and belt conveyors were evaluated according to ammonia, nitrate, nitrogen oxides, sulfate, SO_2, and SO_3 emissions. As it can be seen in Figure 4.1, NO_x emissions were the major emission dominating acidification category for both systems. The second and third were SO_2 and ammonia.



	Ammonia	Nitrate	Nitrogen oxides	Sulfate	Sulfur dioxide	Sulfur trioxide
Off-highway truck	8639.78	3.78	1527887.80	147.51	46070.26	0.00
Belt Conveyor	14275.52	49.60	604870.67	925.26	212480.40	0.00

Figure 4.1 LCA comparison off-highway truck vs. belt conveyor in terms of acidification

NO_2 emission in the transportation phase of diesel oil was the primary actor in acidification where trucks had more environmental load compared to the belt conveyors. Effect of NO_x emission on acidification for off-highway trucks was 1,527,888 PDF m^2 year whereas belt conveyors had an impact of 604,871 PDF m^2 year. This means that potentially disappeared fraction of over space and time of various species is affected more intensively by off-highway trucks. Plants, animals, and other species are potentially endangered per kg of emission.

Off-highway trucks had approximately 1.9 times more acidification impact on the environment compared to the belt conveyors mainly originated from the diesel oil combustion in the utilization phase. Another major emission source in this category for the trucks is the transportation of diesel oil from refinery to the end user.

Process contributions for the belt conveyor in acidification category are illustrated in Figure 4.2.

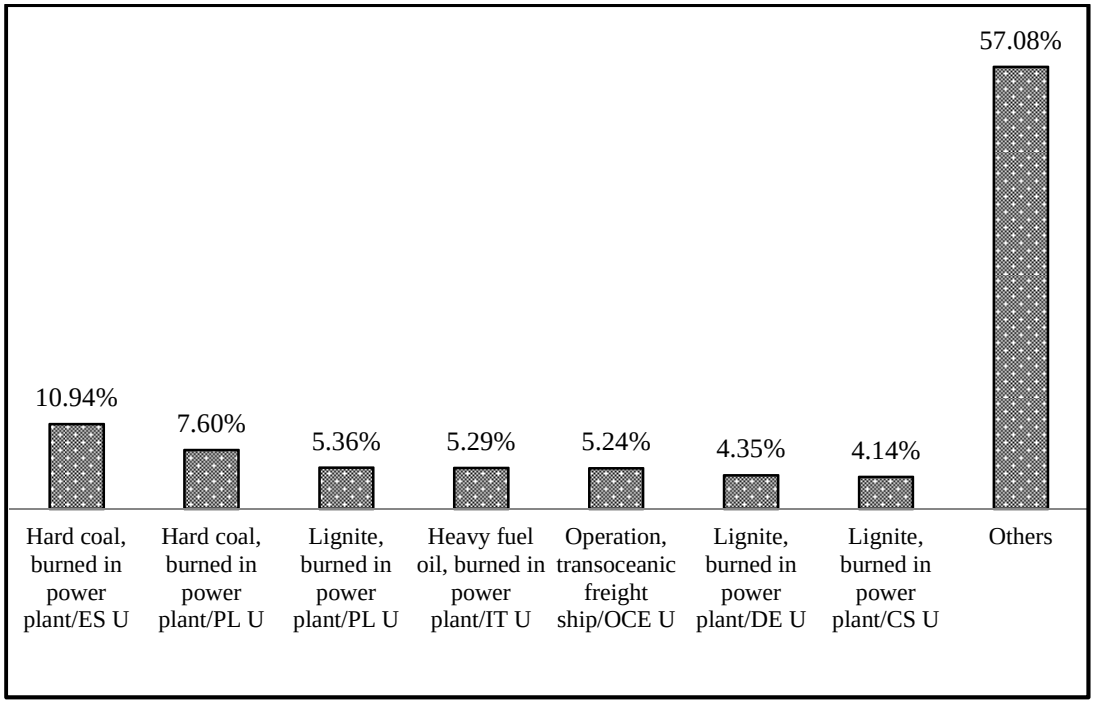


Figure 4.2 Process contributions for belt conveyors in acidification category

The major contributor of acidification was determined as hard coal burned in a power plant in Estonia by 10.94 percent for the belt conveyors. Lignite and heavy fuel oil utilized for electricity generation are other important contributors of the acidification category. A cut-off was used to filter contributions of 519 processes some of which are not meaningful to be considered and represented graphically. Processes grouped under “Others” category with small contributions add up to 57.08 percent, however are not considered as important.

Process contribution of off-highway trucks in acidification category is represented in Figure 4.3.

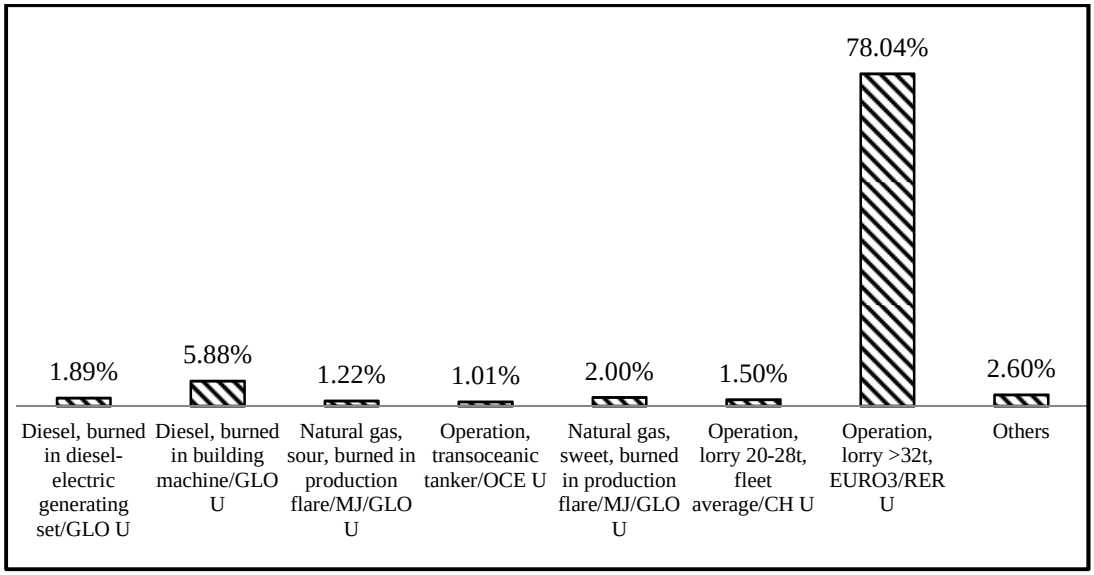


Figure 4.3 Process contributions for off-highway trucks in acidification category

Major contributor of acidification was determined as operation stage of the trucks including diesel oil combustion and had a total share of 78.04 percent. Besides combustion, operation process includes maintenance and construction of the road which cover life cycles of steel and bitumen utilized in road construction. Engine technology was selected to be EURO-3 for the trucks as it is still the most commonly used one in surface mining operations in Turkey.

In order to represent the comparison in a more distinctive way, a threshold of one percent was used for climate change category. This threshold was only used for graphical representation; calculations were conducted without any cut-off criteria analyzing the systems cradle-to-grave. CO_2 equivalent emissions are prominent indicators for the climate change. As illustrated in Figure 4.4, major emissions in this category were CO_2, N_2O, and CH_4.

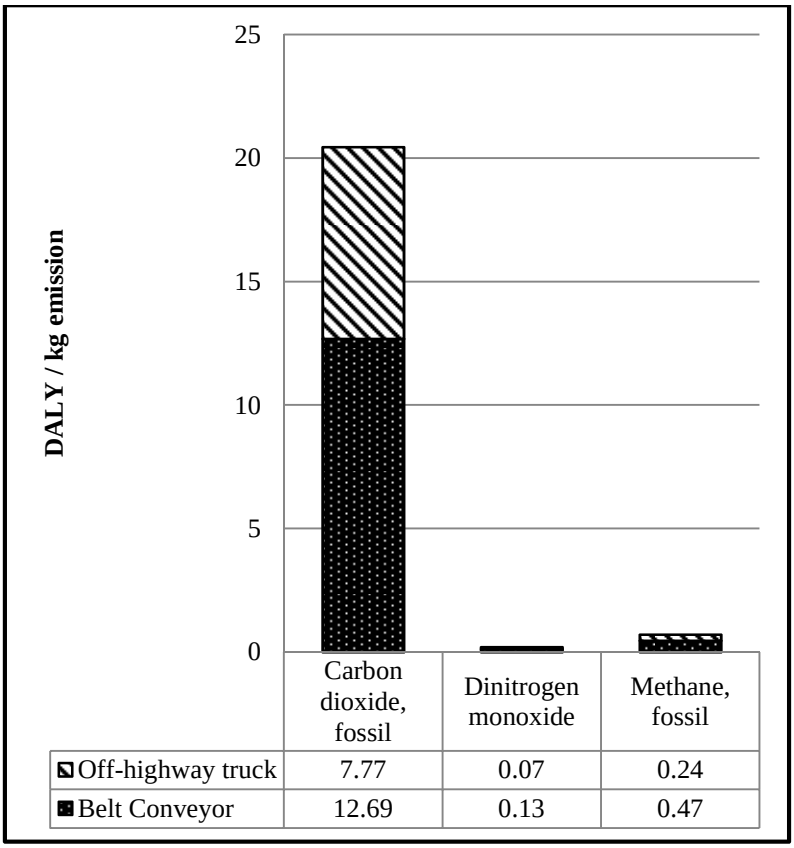


Figure 4.4 LCA comparison of off-highway truck vs. belt conveyor according to climate change

CO_2 emissions were dominant in climate change category for both material handling systems. Belt conveyors had a higher impact on climate change with 12.69 DALY/kg emission as defined by the World Health Organization. Off-highway trucks had a climate change impact of 7.77 DALY/kg emission and 40 percent less burden compared to belt conveyors in this category. The reason for belt conveyors systems being less environmental friendly by means of climate change is considered to be the electricity consumption. The electricity utilized by belt conveyor systems is generated from coal combustion process and is selected from the Eco-invent database as a mixture of European Union member countries where Germany has the highest share followed by Estonia. Thus, major carbon dioxide emission was generated during the combustion of coal (lignite) at the power plant.

Process contributions of belt conveyors in climate change category are illustrated in Figure 4.5.

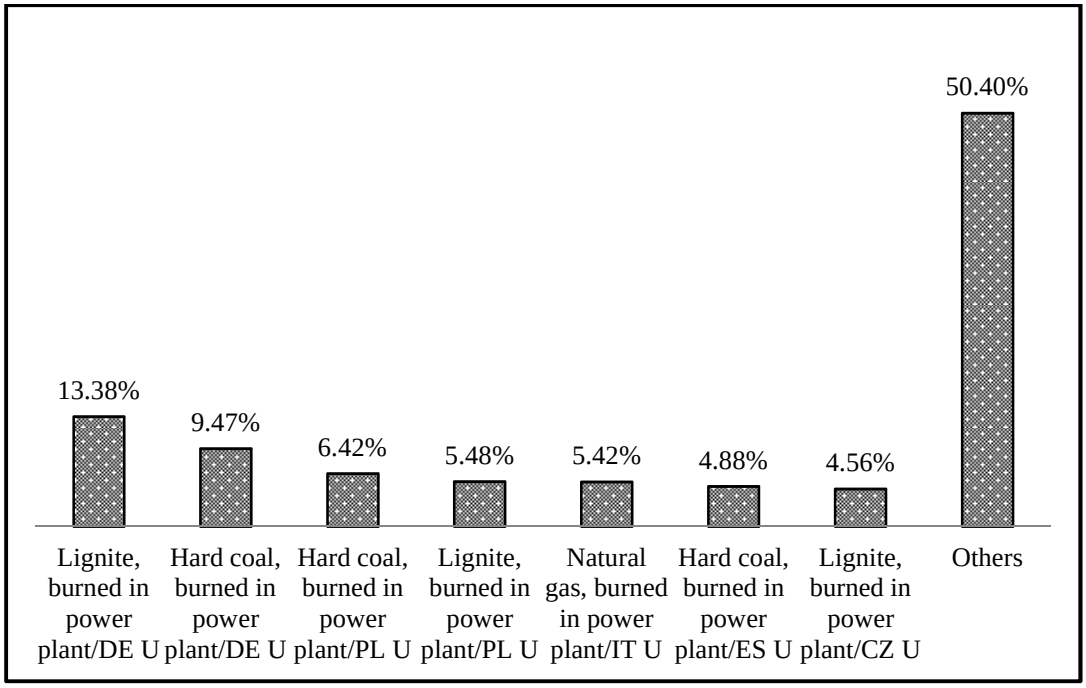


Figure 4.5 Process contributions for belt conveyors in climate change category

Lignite burned in a power plant in Germany is the major contributor for belt conveyors. As EU member countries have different technologies for primary energy generation, environmental load of these countries differ from each other. Another reason for having this difference is the share of renewable energy in the national grid. As it observed in Italy's electricity grid, natural gas is the primary source in electricity generation. Processes grouped under "Others" category with small contributions are not considered as important when compared to major processes, such as coal combustion for electricity generation with higher impact, however, the sum is 50.4 percent.

Off-highway trucks are represented in Figure 4.6 by major process contributors.

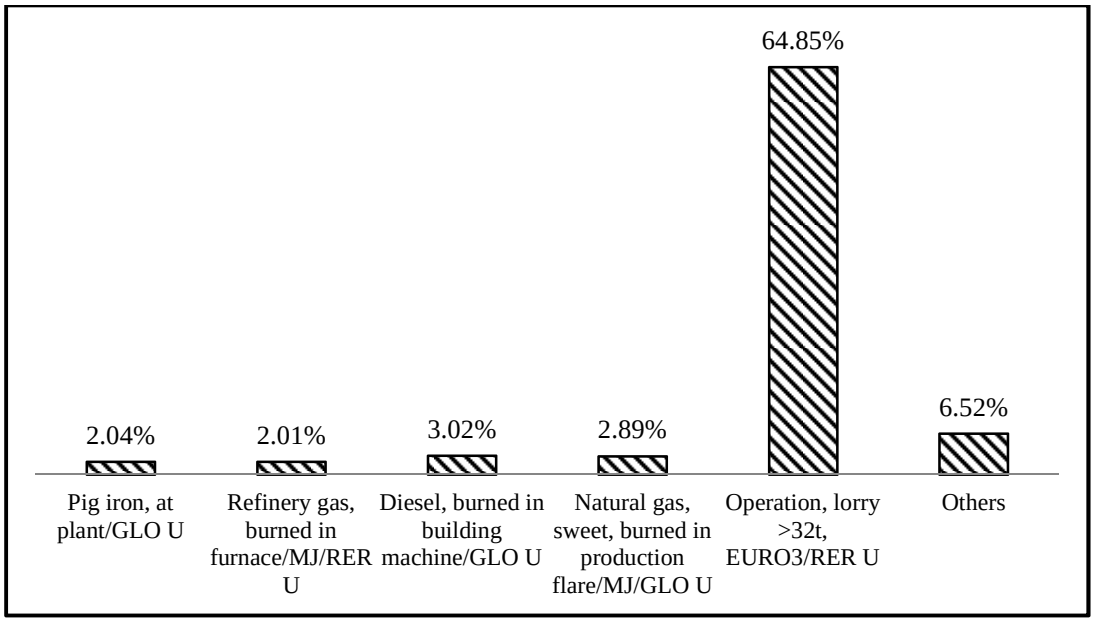


Figure 4.6 Process contributions for off-highway trucks in climate change category

Operation phase was the major contributor in climate change category compared to the manufacturing process. Pig iron in the manufacturing process of the off-highway trucks' steel parts had a contribution of 2.04 percent. Operation of the truck was the main contributor with 64.85 percent in the climate change category. This points out the considerable difference between utilization and manufacturing assemblies in the modelled off-highway truck. Processes such as refinery gas burned in furnace, natural gas vented, and polyethylene HDPE granulate at plant are processes that constitute "Others" category together with 760 processes with small contributions.

4.2 Uncertainty Assessment for the Developed LCA Model

Uncertainty assessment was conducted by Monte Carlo Simulation tool in SIMAPRO software for the LCA comparison of off-highway trucks and belt conveyors. Probability of the results for both off-highway trucks and belt conveyors was determined for both acidification and climate change impact categories. As a

result of the simulation with 10,000 steps summarized in Table 4.1, both impact categories were evaluated by Monte Carlo Simulation.

Table 4.1 Descriptive statistics of uncertainty assessment

Impact category	Mean	Median	SD	CV	Std. err. of mean
Acidification	-752,000	-657,000	580,000	-77.2 %	-0.00772
Climate change	5.22	5.35	3.04	58.3 %	0.00583

Off-highway trucks were identified to have greater impact in acidification category according to the results of the analysis. SO_x and NO_x were determined as major contributors in the off-highway truck utilization assembly. Using the existing uncertainty in the available data in Eco-invent database, it was concluded that off-highway trucks had greater impact than belt conveyors in acidification with 94.5 percent probability. Figure 4.7 represents the uncertainty assessment of the LCA comparison for acidification category.

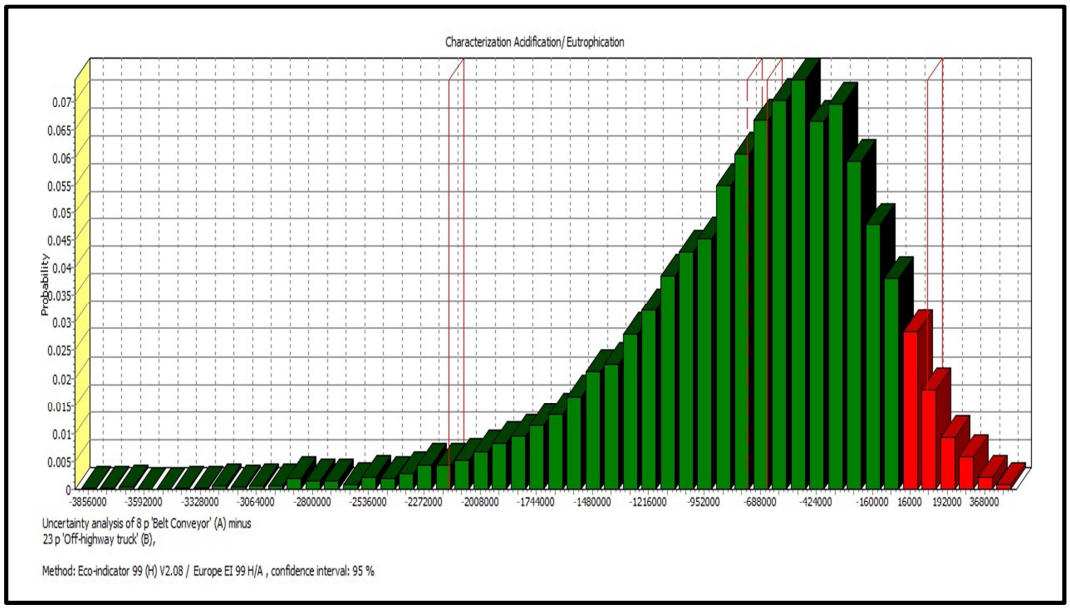


Figure 4.7 Uncertainty assessment of acidification category

In Figure 4.7, off-highway trucks have dominantly greater impact in acidification category compared to belt conveyors. Difference of acidification impacts of off-highway trucks and belt conveyors was evaluated and pointed out the off-highway trucks represented by green color had greater acidification impact with higher probability.

Belt conveyors had greater impact on climate change category compared to off-highway trucks. Uncertainty assessment of climate change category is represented in Figure 4.8.

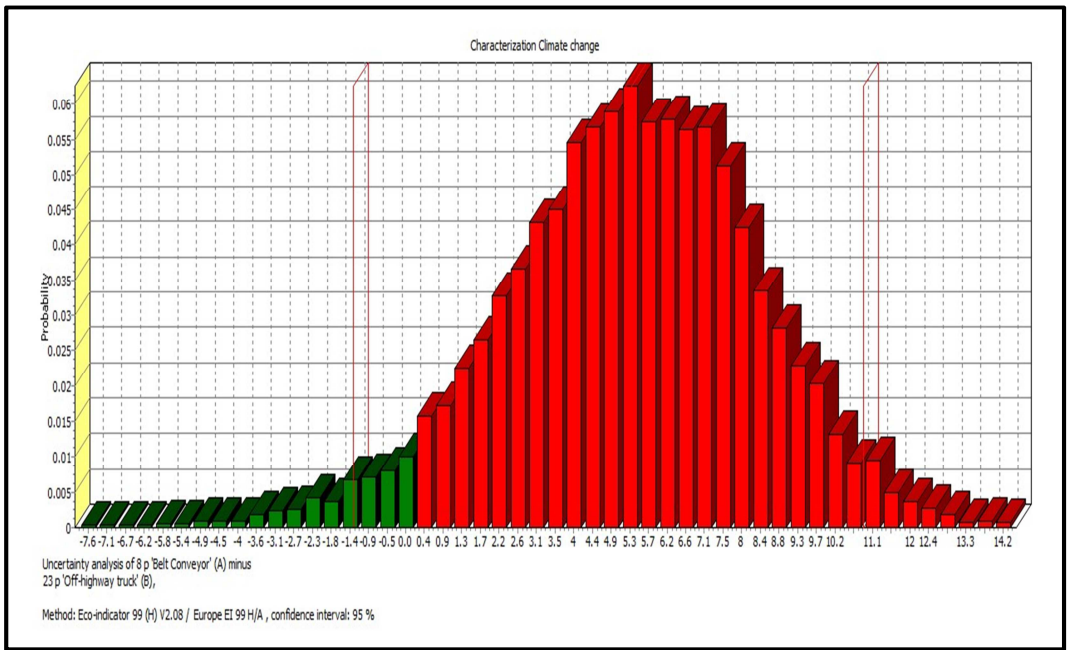


Figure 4.8 Uncertainty assessment of climate change category

In Figure 4.8, belt conveyors, illustrated in red color, had greater impact in climate change category with a probability of 95.2 percent. Difference of climate change effects of off-highway trucks and belt conveyors was considered. Uncertainty assessment was also carried out for CO_2, CH_4, NO_x, and SO_x emissions as illustrated in detail in Appendix-G.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This study implies that technological improvement in fuel combustion and electricity generation is crucial for the improvement of environmental profiles of off-highway trucks and belt conveyors in the mining industry. In addition to this, sulphure content of diesel oil indicated a critical share of off-highway trucks in acidification category which might be overcome by utilizing biofuel with lower sulphure content. As electricity generation from coal power plants is the major climate change sink, renewable alternatives such as solar, wind are recommended to take portion in the national electricity grid. Current fuel combustion technology should be improved for off-highway trucks, whereas, effectiveness of electricity generation from coal plants has to be reconsidered for belt conveyors. Due to the lack of a national database, Eco-invent database was used as the primary data source of data throughout the study to compile relevant data for upstream and downstream processes for both systems. Further studies with more detailed and reliable data should be advanced for more spatial and industry specific conclusions.

Contribution of this research study could be extended to both mining sector and the national emission inventory. As a result of this study, critical stages in haulage of material in an open pit coal mine were stated to be utilization stages. Data acquired and used in comparison will improve the quality of data to represent our national effort spent to reduce greenhouse gas emissions.

Lack of data in most of the indicators and disorganization in available data sources were major issues in this research. This bottleneck is still an emerging issue for

researchers studying environmental burdens in Turkey. This research study will take its place among the literature about this subject in Turkey.

Using LCA as a comparison method in mining industry will make environmental burden a supportive criteria to economic in decision making. Sustainable production of coal is an ultimate goal that will be achieved only by considering environmental load in all stages of production.

Environmental effects of off-highway trucks and belt conveyors were studied according to climate change and acidification categories. The main conclusions derived from this study are:

1. LCA is a supportive decision making tool that could be effectively utilized in the equipment selection process though it is not common in mining industry.

2. Off-highway trucks had 1.9 times greater impact on acidification category than belt conveyors. 96 percent of the acidification effect was caused by NO_x emissions.

3. Climate change impact of belt conveyors was 1.6 times greater than off-highway trucks. CO_2 emissions from fossil fuel combustion led to 95 percent of the climate change effect.

4. Hotspots of environmental load for belt conveyors and off-highway trucks are the utilization phases where electricity and diesel oil are consumed.

5. Eco-invent database was modified and utilized as a primary data source as it was preferred to use a complete data-set instead of publicly accessible databases.

6. Uncertainty assessment was conducted by Monte Carlo Simulation with a stop criterion of 10,000 stages.

The main recommendations for future studies in the same research domain are:.

1. Equipment comparison in the mining industry is a decision making process where no environmental aspects are considered, however, this data should be collected and used as a supportive criteria. Researches about the environmental burden of coal mining have a major importance for Turkey.

2. Turkey being a socio-politically important country both for Europe and Asia needs to develop its own database and tools for studying environmental burdens. Governmental and private sector should be in co-operation to develop Turkey's national emission inventory so that researchers could access primary data for their research.

3. Transportation of the diesel oil might be done using pipelines more intensely so that emissions from highway transportation in this stage could be eliminated.

4. Nitrogen oxide emissions could be reduced by implementing biofuel also with lower sulphure content for off-highway trucks. There will be no additional cost for this implementation as biofuel can be used in the trucks without any modification in engine or oil filter. Environmental performance of biofuel and renewable energy sources should be studied in detail by LCA prior to utilization by off-highway trucks.

5. Share of renewable energy sources such as solar and wind in the electricity grid should be increased in order to reduce environmental load of belt conveyors.

6. Clean coal technologies should be improved and implemented more commonly, thus, environmental burden of electricity generation is reduced. Emissions related to utilization phase of belt conveyors would be reduced by utilization of cleaner electricity.

7. Uncertainty assessment for acidification and climate change categories might not reflect Turkey's situation. Utilized data in analysis and uncertainty assessment was selected as an average for EU member countries, thus, future studies should also focus on sensitivity analysis. Multi-variate statistics may be utilized in further studies to evaluate results of LCA studies.

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APPENDIX A

GHG EMISSIONS OF TURKEY

Table A.1 CO_2 emission according to GHG

CO_2 emission, 1990-2008

GHG SOURCES	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	(1000 tons)									
Energy	**126,701.07**	**132,470.80**	**138,638.26**	**145,246.92**	**143,208.79**	**155,347.30**	**173,367.39**	**185,596.47**	**185,004.09**	**185,203.17**
1. Conversion and Energy	**34,014.69**	**36,632.03**	**41,794.87**	**40,565.29**	**47,175.41**	**47,314.12**	**51,977.07**	**58,188.68**	**64,071.55**	**69,346.15**
a. Electricity Generation	30,325.45	33,036.20	37,958.32	36,117.85	42,458.31	43,750.17	47,289.61	53,229.41	58,893.78	64,542.94
b. Petroleum Refinery	3,689.24	3,595.83	3,836.55	4,447.45	4,717.11	3,563.95	4,687.46	4,959.27	5,177.77	4,803.20
2. Industry	**37,530.74**	**40,470.20**	**39,431.96**	**40,812.57**	**37,079.95**	**41,982.33**	**51,994.65**	**56,994.60**	**55,375.65**	**49,770.12**
3. Transportation	**25,954.63**	**24,674.45**	**25,311.81**	**30,941.64**	**29,380.24**	**32,830.43**	**34,882.59**	**33,270.15**	**31,427.51**	**33,290.61**
4. Other Sectors	**29,201.00**	**30,694.12**	**32,099.62**	**32,927.41**	**29,573.19**	**33,220.43**	**34,513.08**	**37,143.04**	**34,129.38**	**32,796.28**
a. Residential	23,405.61	24,874.02	26,263.78	25,739.30	22,348.39	25,848.03	26,741.60	29,088.06	26,149.96	24,596.65
b. Agriculture/Forestry/Fishery	5,795.38	5,820.11	5,835.84	7,188.11	7,224.80	7,372.41	7,771.48	8,054.98	7,979.42	8,199.64
Industrial Processes	**14,661.34**	**15,838.35**	**15,308.82**	**17,302.86**	**17,609.08**	**18,552.66**	**18,643.76**	**19,581.97**	**19,320.83**	**18,474.75**
1. Minerals	**13,726.00**	**15,002.30**	**14,482.62**	**16,132.29**	**16,644.35**	**17,477.77**	**17,518.83**	**18,429.57**	**18,575.74**	**18,157.58**
2. Chemical Industry	**825.72**	**735.59**	**720.76**	**1,065.27**	**857.18**	**964.17**	**1,013.15**	**1,040.77**	**633.85**	**206.11**
3. Metal Production	**109.62**	**100.47**	**105.45**	**105.3**	**107.56**	**110.72**	**111.78**	**111.64**	**111.25**	**111.07**
Total	**141,362.41**	**148,309.16**	**153,947.08**	**162,549.79**	**160,817.88**	**173,899.96**	**192,011.14**	**205,178.44**	**204,324.92**	**203,677.93**

Table A.1 CO_2 emission according to GHG sources of Turkey (cont'd)

CO_2 emmision, 1990-2008

GHG SOURCES	2000	2001	2002	2003	2004	2005	2006	2007	2008
	(1000 tons)								
Energy	**207,054.44**	**190,878.73**	**198,951.36**	**212,964.27**	**222,283.61**	**236,355.33**	**253,150.17**	**282,833.96**	**270,862.11**
1. Conversion and Energy	**76,779.72**	**79,722.48**	**74,055.79**	**74,195.58**	**76,184.85**	**88,556.87**	**90,602.20**	**106,602.75**	**105,940.85**
a. Electricity Generation	72,089.38	74,515.39	68,814.72	68,973.26	70,499.47	83,679.69	85,311.75	100,661.51	101,473.20
b. Petroleum Refinery	4,690.34	5,207.09	5,241.07	5,222.32	5,685.38	4,877.17	5,290.45	5,941.24	4,467.65
2. Industry	**59,874.86**	**46,893.54**	**58,082.79**	**67,360.25**	**68,302.43**	**67,406.33**	**77,232.58**	**80,374.14**	**55,973.17**
3. Transportation	**34,968.90**	**35,026.30**	**36,044.33**	**37,765.48**	**40,457.82**	**40,525.92**	**43,738.06**	**51,010.66**	**47,048.07**
4. Other Sectors	**35,430.96**	**29,236.41**	**30,768.46**	**33,642.96**	**37,338.52**	**39,866.22**	**41,577.33**	**44,846.42**	**61,900.02**
a. Residential	26,891.55	21,065.09	22,471.30	25,218.56	28,284.91	30,639.47	31,667.43	34,051.06	48,223.92
b. Agriculture/Forestry/Fishery	8,539.41	8,171.33	8,297.17	8,424.40	9,053.60	9,226.75	9,909.91	10,795.35	13,676.10
Industrial Processes	**18,377.83**	**18,111.75**	**18,974.43**	**19,676.86**	**21,150.82**	**23,250.15**	**23,566.26**	**25,081.67**	**26,261.83**
1. Minerals	**18,114.49**	**17,831.22**	**18,248.09**	**18,961.56**	**20,332.97**	**22,549.22**	**23,279.83**	**25,081.67**	**26,261.83**
2. Chemical Industry	**152.64**	**169.42**	**613.84**	**601.65**	**702.64**	**592.93**	**178.42**	**(*)**	**(*)**
3. Metal Production	**110.7**	**111.11**	**112.5**	**113.65**	**115.2**	**108**	**108.01**	**(*)**	**(*)**
Total	**225,432.27**	**208,990.49**	**217,925.80**	**232,641.13**	**243,434.42**	**259,605.48**	**276,716.43**	**307,915.64**	**297,123.94**

Table A.2 CH_4 emission according to GHG sources of Turkey

CH_4 emission, 1990-2008

GHG SOURCES	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	(1000 tons)									
Energy	**211.13**	**213.27**	**219.56**	**212.54**	**207.26**	**206.1**	**208.93**	**217.63**	**210.22**	**199.63**
A. Fuel Combustion	**143.02**	**146.04**	**147.3**	**143.04**	**132.54**	**137.27**	**136.96**	**142**	**132.5**	**124**
1. Conversion and Energy	**0.61**	**0.6**	**0.73**	**0.74**	**0.83**	**0.82**	**0.91**	**1.01**	**1.11**	**1.2**
2. Industry	**3.02**	**3.28**	**3.14**	**3.23**	**2.95**	**3.29**	**4.39**	**4.9**	**4.79**	**4.28**
3. Transportation	**3.37**	**3.25**	**3.63**	**4.24**	**5.1**	**5.63**	**6.05**	**6.36**	**6.44**	**6.54**
4. Other Sectors	**136.03**	**138.91**	**139.8**	**134.83**	**123.66**	**127.53**	**125.61**	**129.72**	**120.15**	**111.97**
a. Residential	135.63	138.51	139.4	134.33	123.16	127.02	125.07	129.17	119.6	111.41
b. Agriculture/Forestry/Fishery	0.4	0.4	0.4	0.5	0.5	0.51	0.54	0.55	0.55	0.56
B. Fugitive Emissions	**68.11**	**67.23**	**72.26**	**69.5**	**74.72**	**68.83**	**71.97**	**75.63**	**77.72**	**75.63**
a. Solid Fuels	68.11	67.23	72.26	69.5	74.72	68.83	71.97	75.63	77.72	75.63
Industrial Processes	**2.35**	**2.33**	**2.28**	**2.13**	**2.17**	**2.34**	**2.39**	**2.42**	**2.35**	**2.22**
2. Chemical Industry	**2.35**	**2.33**	**2.28**	**2.13**	**2.17**	**2.34**	**2.39**	**2.42**	**2.35**	**2.22**
Agriculture	**984.64**	**1,014.68**	**1,002.47**	**989.29**	**983.88**	**957.76**	**957.83**	**894.3**	**887.88**	**896.56**
1. Enteric Fermantation	**902.65**	**932.39**	**923.67**	**908.96**	**897.19**	**876.56**	**876.8**	**818.94**	**803.46**	**807.41**
2. Fertilizers	**68.04**	**69.32**	**66.17**	**66.78**	**74.91**	**68.14**	**67.17**	**61.38**	**68.95**	**74.49**
3. Rice	**5.3**	**4.04**	**4.3**	**4.49**	**4.05**	**5**	**5.49**	**5.5**	**6**	**6.5**
4. Incineration of agricultural waste	**8.66**	**8.93**	**8.33**	**9.06**	**7.74**	**8.06**	**8.37**	**8.48**	**9.47**	**8.17**
Waste	**397.01**	**558.35**	**729.05**	**859.24**	**888.14**	**1,065.54**	**1,179.14**	**1,294.81**	**1,370.91**	**1,432.17**
1. Solid Waste Management	**304.12**	**463.89**	**633.01**	**761.65**	**790.22**	**967.32**	**1,080.69**	**1,196.15**	**1,270.85**	**1,331.98**
a. Regular Storage	0	0	62.29	62.29	62.29	111.18	219.22	336.01	404.86	479.89
b. Irregular Storage	304.12	463.89	570.72	699.36	727.92	856.14	861.47	860.14	865.99	852.09
2. Wastewater	**92.89**	**94.46**	**96.03**	**97.6**	**97.93**	**98.21**	**98.46**	**98.65**	**100.07**	**100.19**
a. Residential and Industrial wastewaters	92.89	94.46	96.03	97.6	97.93	98.21	98.46	98.65	100.07	100.19
Total	**1,595.13**	**1,788.63**	**1,953.36**	**2,063.21**	**2,081.45**	**2,231.74**	**2,348.30**	**2,409.15**	**2,471.37**	**2,530.59**

Table A.2 CH_4 emission according to GHG sources of Turkey (cont'd)

CH_4 emission, 1990-2008

GHG SOURCES	2000	2001	2002	2003	2004	2005	2006	2007	2008
	(1000 ton)								
Energy	**199.45**	**186.17**	**180.38**	**175.61**	**174.48**	**184.98**	**190.3**	**203.37**	**252.52**
A. Fuel Combustion	**122.46**	**109.01**	**111.65**	**114.08**	**115.94**	**114.38**	**113.31**	**115.89**	**160.28**
1. Conversion and Energy	**1.42**	**1.47**	**1.42**	**1.41**	**1.41**	**1.5**	**1.51**	**1.75**	**1.67**
2. Industry	**5.36**	**4.03**	**5.14**	**6**	**6.15**	**6.1**	**7.25**	**7.8**	**5.35**
3. Transportation	**6.47**	**6.09**	**5.89**	**5.92**	**5.97**	**5.84**	**5.93**	**6.06**	**5.97**
4. Other Sectors	**109.21**	**97.42**	**99.21**	**100.76**	**102.41**	**100.95**	**98.63**	**100.28**	**147.28**
a. Residential	108.62	96.86	98.64	100.18	101.78	100.32	97.95	99.55	146.35
b. Agriculture/Forestry/Fishery	0.59	0.56	0.57	0.58	0.62	0.63	0.68	0.74	0.93
B. Fugitive Emissions	**76.99**	**77.16**	**68.73**	**61.53**	**58.54**	**70.6**	**76.99**	**87.48**	**92.24**
a. Solid Fuels	76.99	77.16	68.73	61.53	58.54	70.6	76.99	87.48	92.24
Industrial Processes	**2.25**	**2.06**	**2.15**	**2.46**	**2.46**	**0.71**	**2.5**	**2.56**	**2.64**
2. Chemical Industry	**2.25**	**2.06**	**2.15**	**2.46**	**2.46**	**0.71**	**2.5**	**2.56**	**2.64**
Agriculture	**853.13**	**836.57**	**765.82**	**782.53**	**762.35**	**790.69**	**813.84**	**821.92**	**797.52**
1. Enteric Fermantation	**775.87**	**753.94**	**696.52**	**709.51**	**695.55**	**718.24**	**740.78**	**745.83**	**725.72**
2. Fertilizers	**62.26**	**68.34**	**54.51**	**57.88**	**50.25**	**53.98**	**53.69**	**58.76**	**54.03**
3. Rice	**5.8**	**5.9**	**6**	**6.5**	**7**	**8.5**	**9.91**	**9.39**	**9.95**
4. Incineration of agricultural waste	**9.21**	**8.4**	**8.79**	**8.64**	**9.55**	**9.98**	**9.46**	**7.93**	**7.81**
Waste	**1,483.25**	**1,486.61**	**1,453.00**	**1,498.15**	**1,411.77**	**1,516.66**	**1,532.76**	**1,618.97**	**1,532.78**
1. Solid Waste Management	**1,382.98**	**1,386.33**	**1,352.75**	**1,397.97**	**1,311.72**	**1,416.78**	**1,431.66**	**1,516.65**	**1,436.66**
a. Regular Storage	548.83	639.42	543.73	572.25	539.12	545.02	725.73	725.73	842.95
b. Irregular Storage	834.15	746.91	809.02	825.72	772.6	871.76	705.94	790.93	593.7
2. Wastewater	**100.27**	**100.28**	**100.25**	**100.17**	**100.05**	**99.88**	**101.1**	**102.32**	**96.12**
a. Residential and Industrial wastewaters	100.27	100.28	100.25	100.17	100.05	99.88	101.1	102.32	96.12
Total	**2,538.09**	**2,511.42**	**2,401.35**	**2,458.75**	**2,351.07**	**2,493.04**	**2,539.39**	**2,646.81**	**2,585.47**

Table A.3 N_2O emission according to GHG sources of Turkey

N_2O emission, 1990-2008

GHG SOURCES	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	(1000 ton)									
Energy	**3.21**	**3.25**	**3.29**	**3.44**	**3.43**	**3.59**	**3.89**	**3.94**	**3.88**	**3.93**
1. Conversion and Energy	**0.37**	**0.41**	**0.48**	**0.45**	**0.53**	**0.52**	**0.58**	**0.64**	**0.69**	**0.71**
a. Electricity Generation	0.34	0.38	0.44	0.42	0.5	0.49	0.54	0.6	0.65	0.67
b. Petroleum Refinery	0.03	0.03	0.03	0.04	0.04	0.03	0.04	0.04	0.04	0.04
2. Industry	**0.45**	**0.49**	**0.46**	**0.46**	**0.43**	**0.47**	**0.62**	**0.67**	**0.67**	**0.6**
a. Steel	0.13	0.13	0.13	0.13	0.13	0.13	0.15	0.15	0.13	0.13
b. Non-metallic reserves	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
c. Chemicals	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
d. Others	0.29	0.33	0.3	0.3	0.27	0.3	0.44	0.49	0.5	0.43
3. Transportation	**0.84**	**0.8**	**0.79**	**0.97**	**0.98**	**1.08**	**1.19**	**1.1**	**1.04**	**1.21**
a. Air way	0.03	0.03	0.04	0.05	0.05	0.09	0.1	0.1	0.1	0.1
b. Highway	0.8	0.75	0.74	0.9	0.9	0.97	1.07	0.98	0.91	1.09
c. Railway	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
d. Marine	0	0	0	0.01	0	0.01	0.01	0.01	0.01	0.01
4. Other Sectors	**1.54**	**1.55**	**1.56**	**1.55**	**1.49**	**1.52**	**1.51**	**1.53**	**1.47**	**1.41**
a. Residential	1.49	1.5	1.51	1.49	1.43	1.46	1.44	1.46	1.41	1.34
b. Agriculture/Forestry/Fishery	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07
Industrial Processes	**0.41**	**3.55**	**9.32**	**9.31**	**3.19**	**16.41**	**15.25**	**10.9**	**13.56**	**14.11**
a. Chemicals	0.41	3.55	9.32	9.31	3.19	16.41	15.25	10.9	13.56	14.11
Agriucultural Processes	**29.35**	**29.16**	**29.94**	**31.41**	**27.52**	**27.63**	**28.99**	**28.64**	**31.34**	**31.57**
a. Fertilizers	8.06	8.46	8.44	8.41	8.37	8.12	8.19	7.75	7.73	7.72
b. Agricultural land	21.12	20.52	21.34	22.82	18.99	19.35	20.63	20.73	23.42	23.68
c. Incineration of agricultural waste	0.17	0.18	0.17	0.18	0.16	0.16	0.17	0.17	0.19	0.17
Waste Management	**4.34**	**4.41**	**4.48**	**4.56**	**4.63**	**4.7**	**4.77**	**4.85**	**4.92**	**4.99**
1. Wastewater	**4.34**	**4.41**	**4.48**	**4.56**	**4.63**	**4.7**	**4.77**	**4.85**	**4.92**	**4.99**
Total	**37.31**	**40.36**	**47.03**	**48.71**	**38.77**	**52.34**	**52.91**	**48.34**	**53.7**	**54.6**

Table A.3 N_2O emission according to GHG sources of Turkey (cont'd)

N_2O emission, 1990-2008

GHG SOURCES	2000	2001	2002	2003	2004	2005	2006	2007	2008
	(1000 ton)								
Energy	**4.2**	**3.97**	**4.13**	**4.36**	**4.78**	**4.89**	**4.57**	**5.12**	**4.97**
1. Conversion and Energy	**0.75**	**0.76**	**0.67**	**0.65**	**0.67**	**0.79**	**0.81**	**0.94**	**0.96**
a. Electricity Generation	0.71	0.72	0.62	0.6	0.62	0.75	0.77	0.9	0.93
b. Petroleum Refinery	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.03
2. Industry	**0.75**	**0.55**	**0.7**	**0.79**	**0.8**	**0.76**	**0.88**	**0.92**	**0.6**
a. Steel	0.14	0.13	0.12	0.14	0.14	0.14	0.14	0.15	0.17
b. Non-metallic reserves	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.03	0
c. Chemicals	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0
d. Others	0.57	0.38	0.53	0.62	0.63	0.59	0.71	0.73	0.43
3. Transportation	**1.33**	**1.39**	**1.5**	**1.69**	**2.08**	**2.12**	**1.71**	**2.1**	**2.04**
a. Air way	0.1	0.11	0.12	0.13	0.16	0.03	0.04	0.19	0.18
b. Highway	1.21	1.27	1.37	1.54	1.91	2.07	1.64	1.87	1.82
c. Railway	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
d. Marine	0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4. Other Sectors	**1.38**	**1.27**	**1.26**	**1.24**	**1.23**	**1.21**	**1.17**	**1.16**	**1.38**
a. Residential	1.31	1.21	1.19	1.17	1.16	1.13	1.08	1.07	1.26
b. Agriculture/Forestry/Fishery	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.09	0.11
Industrial Processes	**13.85**	**11.2**	**12.89**	**12.14**	**12.46**	**5.68**	**9.77**	**(*)**	**(*)**
a. Chemicals	13.85	11.2	12.89	12.14	12.46	5.68	9.77	(*)	(*)
Agriucultural Processes	**30.5**	**27.07**	**27.2**	**28.79**	**29.04**	**29.79**	**30.36**	**29.19**	**26.76**
a. Fertilizers	7.51	7.28	6.83	6.93	7.01	7.3	7.56	7.47	7.28
b. Agricultural land	22.8	19.62	20.19	21.69	21.83	22.28	22.61	21.56	19.32
c. Incineration of agricultural waste	0.19	0.17	0.18	0.18	0.19	0.2	0.19	0.16	0.16
Waste Management	**5.06**	**5.13**	**5.19**	**5.26**	**5.33**	**5.4**	**5.46**	**5.53**	**5.59**
1. Wastewater	**5.06**	**5.13**	**5.19**	**5.26**	**5.33**	**5.4**	**5.46**	**5.53**	**5.59**
Total	**53.6**	**47.37**	**49.42**	**50.56**	**51.61**	**45.75**	**50.16**	**39.84**	**37.33**

Table A.4 NO_x emission according to GHG sources of Turkey

NO_x emission, 1990-2008

GHG SOURCES	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	(1000 ton)									
Energy	**628.65**	**634.17**	**652.98**	**723.75**	**743.43**	**789.51**	**869.29**	**897.78**	**888.57**	**920.2**
1. Conversion and Energy	**99.33**	**107.47**	**122.81**	**118.87**	**138.5**	**138.56**	**152.24**	**170.4**	**187.33**	**201.79**
a. Electricity Generation	89.16	97.56	112.24	106.61	125.5	128.74	139.33	156.73	173.07	188.56
b. Petroleum Refinery	10.16	9.91	10.57	12.25	12.99	9.82	12.91	13.66	14.26	13.23
2. Industry	**112.73**	**121.53**	**117.84**	**121.73**	**111.11**	**124.99**	**157.43**	**172.65**	**168.44**	**151.27**
a. Steel	29.6	30.18	29.93	29.51	29.03	30.37	33.67	33.75	30.49	30.25
b. Non-metallic reserves	2.89	2.66	2.79	2.57	3.46	4.75	3.68	3.35	3.09	4.74
c. Chemicals	7.07	6.55	6.88	7.96	7.12	7.66	7.45	8.38	6.88	8.36
d. Others	73.18	82.14	78.24	81.69	71.5	82.21	112.63	127.16	127.98	107.93
3. Transportation	**263.31**	**249.87**	**255.16**	**304.31**	**318.34**	**344.01**	**370.69**	**358.99**	**341.79**	**375.26**
a. Air way	2.92	3.28	4.1	4.58	5.13	8.67	9.47	10.2	10.52	9.47
b. Highway	238.41	223.73	227.04	273.19	286.61	306.77	332.83	320.44	302.21	338.02
c. Railway	12.04	12.26	11.59	13.6	14.41	14.41	14.73	14.71	14.86	14.86
d. Marine	9.93	10.6	12.43	12.95	12.19	14.16	13.65	13.63	14.2	12.91
4. Other Sectors	**153.28**	**155.31**	**157.18**	**178.84**	**175.48**	**181.95**	**188.93**	**195.74**	**191**	**191.87**
a. Residential	57.49	59.11	60.72	60.03	56.06	60.09	60.47	62.6	59.11	56.34
b. Agriculture/Forestry/Fishery	95.79	96.2	96.46	118.81	119.42	121.86	128.45	133.14	131.89	135.53
Industrial Processes	**10.94**	**12.63**	**13.12**	**13.35**	**9.44**	**20.63**	**21.1**	**19.73**	**21.89**	**20.99**
a. Minerals	8.72	8.54	5.29	5.5	5.41	8.12	9.39	10.64	11.09	9.99
b. Chemicals	0.27	2.25	5.9	5.89	2.03	10.38	9.65	6.9	8.58	8.92
c. Ore resources	0.17	0.15	0.16	0.16	0.16	0.15	0.16	0.17	0.16	0.15
d. Other production	0.43	0.36	0.4	0.3	0.38	0.38	0.34	0.44	0.46	0.38
e. Others	1.35	1.33	1.37	1.51	1.47	1.59	1.56	1.57	1.6	1.54
Agricultural Processes	**4.12**	**4.25**	**3.97**	**4.32**	**3.68**	**3.83**	**3.98**	**4.04**	**4.5**	**3.9**
a. Incineration of agricultural waste	4.12	4.25	3.97	4.32	3.68	3.83	3.98	4.04	4.5	3.9
Total	**643.71**	**651.05**	**670.07**	**741.42**	**756.56**	**813.97**	**894.37**	**921.54**	**914.96**	**945.08**

Table A.4 NO_x emission according to GHG sources of Turkey (cont'd)

NO_x emission, 1990-2008

GHG SOURCES	2000	2001	2002	2003	2004	2005	2006	2007	2008
	(1000 ton)								
Energy	**1,009.66**	**969.21**	**1,000.92**	**1,061.18**	**1,117.47**	**1,049.19**	**1,088.29**	**1,175.51**	**1,269.66**
1. Conversion and Energy	**221.96**	**230.09**	**212.56**	**213.22**	**219.59**	**182.44**	**212.3**	**217.99**	**325.24**
a. Electricity Generation	209.03	215.75	198.13	198.83	203.93	169.4	198.14	202.09	313.24
b. Petroleum Refinery	12.92	14.34	14.44	14.39	15.66	13.04	14.16	15.9	11.99
2. Industry	**183.87**	**142.02**	**177.01**	**204.57**	**207.97**	**203.26**	**233.86**	**244.04**	**168.9**
a. Steel	31.9	29.66	28.16	30.38	30.3	29.86	29.12	32.25	40.26
b. Non-metallic reserves	5.58	5.61	6.11	5.46	6.34	6.46	7.43	27.08	0.71
c. Chemicals	8.72	9.1	9.03	8.58	8.61	11.58	11.83	6.49	1.33
d. Others	137.67	97.66	133.71	160.15	162.73	155.36	185.48	178.22	126.6
3. Transportation	**405.1**	**412.04**	**423.35**	**451.87**	**486.24**	**456.04**	**425.06**	**480.92**	**480.91**
a. Air way	10.29	11.1	11.68	14.45	16.81	14.37	16.84	23.91	22.84
b. Highway	371.43	376.34	386.59	410.63	436.31	406.75	363.16	418.29	419.94
c. Railway	11.13	8.8	8.85	9.2	8.72	9.09	15.9	6.87	7.3
d. Marine	12.25	15.8	16.23	17.6	24.4	25.84	29.15	31.86	30.84
4. Other Sectors	**198.73**	**185.05**	**187.99**	**191.53**	**203.67**	**207.44**	**217.07**	**232.57**	**294.61**
a. Residential	57.58	49.99	50.85	52.28	54.03	56.45	54.89	55.9	70.79
b. Agriculture/Forestry/Fishery	141.15	135.06	137.14	139.25	149.65	151	162.18	176.67	223.81
Industrial Processes	**22.88**	**20.96**	**19.69**	**20.38**	**20.4**	**18.3**	**20.57**	**15.12**	**15.25**
a. Minerals	12.16	11.91	9.45	10.76	10.56	12.79	12.36	13.23	13.67
b. Chemicals	8.76	7.09	8.16	7.68	7.88	3.6	6.18	0.02	0.01
c. Ore resources	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.02	0.01
d. Other production	0.39	0.29	0.29	0.08	0.15	0.14	0.21	0.22	-
e. Others	1.43	1.52	1.65	1.7	1.66	1.63	1.67	1.63	1.55
Agricultural Processes	**4.38**	**4**	**4.18**	**4.14**	**4.57**	**4.81**	**4.55**	**3.83**	**3.8**
a. Incineration of agricultural waste	4.38	4	4.18	4.14	4.57	4.81	4.55	3.83	3.8
Total	**1,036.93**	**994.17**	**1,024.78**	**1,085.70**	**1,142.44**	**1,072.30**	**1,113.42**	**1,194.47**	**1,288.71**

Table A.5 CO emission according to GHG sources of Turkey

CO emission, 1990-2008

GHG SOURCES	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	(1000 ton)									
Energy	**3,445.45**	**3,422.75**	**3,593.41**	**3,891.86**	**4,294.52**	**4,491.64**	**4,609.80**	**4,723.85**	**4,649.10**	**4,438.16**
1. Conversion and Energy	**7.76**	**8.39**	**9.37**	**9.1**	**10.57**	**10.82**	**11.83**	**13.36**	**14.85**	**16.61**
a. Electricity Generation	7	7.65	8.58	8.18	9.6	10.08	10.86	12.33	13.78	15.62
b. Petroleum Refinery	0.76	0.74	0.79	0.92	0.97	0.74	0.97	1.02	1.07	0.99
2. Industry	**40.68**	**43.88**	**40.88**	**41.43**	**38.19**	**41.62**	**58.02**	**64.56**	**64.12**	**56.98**
a. Steel	12.66	12.78	12.38	12.15	12.15	12.97	14.44	14.6	13.09	13.25
b. Non-metallic reserves	0.48	0.36	0.41	0.4	0.61	0.95	0.55	0.59	0.54	0.89
c. Chemicals	1.07	0.55	0.57	1.02	0.87	0.72	0.7	0.91	0.62	0.92
d. Others	26.46	30.19	27.51	27.86	24.56	26.98	42.33	48.45	49.87	41.93
3. Transportation	**1,513.51**	**1,467.03**	**1,634.33**	**1,955.46**	**2,438.28**	**2,610.13**	**2,720.35**	**2,797.24**	**2,790.96**	**2,670.22**
a. Air way	2.82	2.85	4.51	4.09	4.55	7.53	8.16	8.47	8.64	7.4
b. Highway	1,499.83	1,452.81	1,617.45	1,937.96	2,420.54	2,588.10	2,697.91	2,774.51	2,767.64	2,648.99
c. Railway	4.23	4.31	4.07	4.78	5.06	5.06	5.18	5.17	5.22	5.22
d. Marine	6.62	7.07	8.29	8.63	8.13	9.44	9.1	9.09	9.46	8.61
4. Other Sectors	**1,883.51**	**1,903.45**	**1,908.84**	**1,885.86**	**1,807.48**	**1,829.08**	**1,819.59**	**1,848.69**	**1,779.17**	**1,694.34**
a. Residential	1,803.68	1,823.29	1,828.46	1,786.85	1,707.96	1,727.53	1,712.55	1,737.74	1,669.26	1,581.40
b. Agriculture/Forestry/Fishery	79.83	80.17	80.38	99.01	99.52	101.55	107.05	110.95	109.91	112.94
Industrial Processes	**16.46**	**15.23**	**15.7**	**17.35**	**16.62**	**17.78**	**17.98**	**18.64**	**16.35**	**13.67**
a. Minerals	0.01	0.01	0.01	0.02	0.01	0.05	0.06	0.07	0.1	0.06
b. Chemicals	3.83	3.67	3.54	5.4	4.26	5.03	5.17	5.32	3.22	1.06
c. Ore resources	8.87	8.06	8.44	8.4	8.59	8.74	8.98	9.08	8.76	8.67
d. Other production	1.6	1.36	1.5	1.12	1.41	1.42	1.27	1.66	1.72	1.42
e. Others	2.17	2.12	2.19	2.42	2.35	2.54	2.49	2.51	2.55	2.46
Agricultural Processes	**182.03**	**187.75**	**175.16**	**190.52**	**162.66**	**169.4**	**175.99**	**178.26**	**199.01**	**171.68**
Total	**3,643.94**	**3,625.73**	**3,784.27**	**4,099.73**	**4,473.80**	**4,678.82**	**4,803.76**	**4,920.76**	**4,864.46**	**4,623.51**

Table A.5 CO emission according to GHG sources of Turkey (cont'd)

CO emission, 1990-2008

GHG SOURCES	2000	2001	2002	2003	2004	2005	2006	2007	2008
	(1000 ton)								
Energy	**4,090.47**	**3,691.24**	**3,604.69**	**3,511.87**	**3,407.55**	**3,036.11**	**3,141.82**	**3,093.49**	**2,702.07**
1. Conversion and Energy	**18.73**	**19.71**	**18.74**	**19.24**	**19.87**	**23.14**	**23.73**	**28.13**	**28.22**
a. Electricity Generation	17.76	18.64	17.66	18.16	18.69	22.16	22.64	26.73	27.16
b. Petroleum Refinery	0.97	1.08	1.08	1.08	1.17	0.98	1.09	1.39	1.06
2. Industry	**73.44**	**52.73**	**68.31**	**78.17**	**80.39**	**78.04**	**93.18**	**100.33**	**66.82**
a. Steel	14.03	13.01	12.38	13.53	13.84	14.34	14.37	16.06	18.41
b. Non-metallic reserves	1.29	1.31	1.43	1.05	1.26	1.24	1.43	5.96	0.14
c. Chemicals	0.98	1.07	1.09	0.8	0.81	1.55	1.76	1.31	0.29
d. Others	57.14	37.34	53.41	62.78	64.49	60.91	75.61	77	47.99
3. Transportation	**2,350.43**	**2,084.28**	**1,998.83**	**1,911.18**	**1,811.90**	**1,473.43**	**1,591.85**	**1,532.09**	**845.57**
a. Air way	8.02	8.57	9.61	10.22	11.91	10	11.07	14.5	14.6
b. Highway	2,330.33	2,062.09	1,975.29	1,886.00	1,780.66	1,443.01	1,555.75	1,490.63	804.33
c. Railway	3.91	3.09	3.11	3.23	3.06	3.19	5.59	5.72	6.08
d. Marine	8.17	10.53	10.82	11.73	16.27	17.22	19.43	21.24	20.56
4. Other Sectors	**1,647.86**	**1,534.52**	**1,518.81**	**1,503.29**	**1,495.39**	**1,461.51**	**1,433.06**	**1,432.94**	**1,761.45**
a. Residential	1,530.24	1,421.97	1,404.52	1,387.25	1,370.69	1,335.68	1,297.92	1,285.71	1,574.94
b. Agriculture/Forestry/Fishery	117.62	112.55	114.29	116.04	124.71	125.83	135.15	147.22	186.51
Industrial Processes	**13.37**	**13.26**	**15.7**	**15.04**	**15.64**	**14.79**	**13.17**	**4.37**	**3**
a. Minerals	0.07	0.05	0.07	0.07	0.07	0.09	0.12	0.13	0.12
b. Chemicals	0.86	0.98	3.26	3.17	3.43	3.2	1.26	0.4	0.2
c. Ore resources	8.72	8.69	8.67	8.76	8.92	8.36	8.33	0.38	0.18
d. Other production	1.44	1.1	1.07	0.32	0.56	0.53	0.79	0.84	-
e. Others	2.28	2.43	2.64	2.73	2.65	2.61	2.67	2.61	2.49
Agricultural Processes	**193.52**	**176.64**	**184.7**	**181.68**	**200.74**	**209.71**	**198.89**	**166.75**	**164.28**
Total	**4,297.36**	**3,881.14**	**3,805.09**	**3,708.60**	**3,623.93**	**3,260.61**	**3,353.89**	**3,264.60**	**2,869.35**

Table A.6 NMVOC emission according to GHG sources of Turkey

NMVOC emission, 1990-2008

GHG SOURCES	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	(1000 ton)									
Energy	**445.99**	**445.61**	**472.2**	**515.23**	**572.99**	**610.59**	**637.46**	**654.21**	**649.92**	**634.04**
1. Conversion and Energy	**2.06**	**2.2**	**2.49**	**2.44**	**2.81**	**2.86**	**3.14**	**3.53**	**3.92**	**4.36**
a. Electricity Generation	1.81	1.95	2.22	2.13	2.49	2.61	2.81	3.19	3.56	4.02
b. Petroleum Refinery	0.25	0.25	0.26	0.31	0.32	0.25	0.32	0.34	0.36	0.33
2. Industry	**6.04**	**6.5**	**6.13**	**6.25**	**5.75**	**6.33**	**8.5**	**9.4**	**9.29**	**8.28**
a. Steel	1.78	1.8	1.75	1.73	1.72	1.82	2.02	2.04	1.83	1.84
b. Non-metallic reserves	0.1	0.09	0.09	0.09	0.13	0.18	0.12	0.12	0.11	0.17
c. Chemicals	0.24	0.18	0.19	0.25	0.22	0.22	0.21	0.25	0.2	0.25
d. Others	3.91	4.44	4.1	4.19	3.68	4.11	6.14	6.99	7.15	6.02
3. Transportation	**211**	**207.96**	**234.05**	**277.68**	**343.55**	**378.26**	**403.18**	**415.44**	**418.13**	**412.13**
a. Air way	0.69	0.55	1.27	0.78	0.82	1.38	1.45	1.44	1.41	1.08
b. Highway	208.09	205.09	230.27	274.17	340.03	373.92	398.83	411.09	413.72	408.23
c. Railway	0.89	0.91	0.86	1.01	1.07	1.07	1.09	1.09	1.1	1.1
d. Marine	1.32	1.41	1.66	1.73	1.63	1.89	1.82	1.82	1.89	1.72
4. Other Sectors	**226.89**	**228.95**	**229.52**	**228.86**	**220.88**	**223.15**	**222.64**	**225.84**	**218.59**	**209.27**
a. Residential	210.92	212.92	213.45	209.05	200.98	202.84	201.23	203.65	196.61	186.68
b. Agriculture/Forestry/Fishery	15.97	16.03	16.08	19.8	19.9	20.31	21.41	22.19	21.98	22.59
Industrial Processes	**39.76**	**42.2**	**40.36**	**42.84**	**41.38**	**352.52**	**426.13**	**471.24**	**627.51**	**447.85**
a. Minerals	0.09	0.22	0.22	0.32	0.21	312.89	380.48	423.14	575.74	402.73
b. Chemicals	8.84	8.77	8.1	9.44	8.39	9.66	9.98	10.11	9.02	7.02
c. Ore resources	0.05	0.04	0.05	0.04	0.04	0.04	0.05	0.06	0.04	0.03
d. Other production	25.02	27.51	26.16	26.61	26.49	23.17	29	31.25	35.92	31.53
e. Others	5.75	5.64	5.83	6.42	6.24	6.76	6.61	6.68	6.78	6.54
Total	**485.74**	**487.80**	**512.56**	**558.07**	**614.36**	**963.11**	**1,063.58**	**1,125.44**	**1,277.44**	**1,081.89**

Table A.6 NMVOC emission according to GHG sources of Turkey (cont'd)

NMVOC emission, 1990-2008

GHG SOURCES	2000	2001	2002	2003	2004	2005	2006	2007	2008
	(1000 ton)								
Energy	**588.01**	**538.27**	**524.29**	**516.27**	**509.1**	**459.78**	**485.26**	**489.98**	**517.11**
1. Conversion and Energy	**4.95**	**5.2**	**4.95**	**5.06**	**5.2**	**5.98**	**6.11**	**7.19**	**7.2**
a. Electricity Generation	4.63	4.84	4.59	4.7	4.81	5.66	5.76	6.77	6.88
b. Petroleum Refinery	0.32	0.36	0.36	0.36	0.39	0.33	0.36	0.43	0.32
2. Industry	**10.48**	**7.69**	**9.83**	**11.25**	**11.52**	**11.17**	**13.15**	**13.98**	**9.4**
a. Steel	1.95	1.81	1.72	1.87	1.9	1.94	1.92	2.14	2.5
b. Non-metallic reserves	0.22	0.23	0.25	0.2	0.23	0.23	0.26	0.97	0.02
c. Chemicals	0.26	0.27	0.27	0.24	0.24	0.35	0.37	0.22	0.05
d. Others	8.05	5.38	7.59	8.95	9.16	8.66	10.6	10.66	6.83
3. Transportation	**368.53**	**334.3**	**320.82**	**313.61**	**306.85**	**261.22**	**287.46**	**289.89**	**285.59**
a. Air way	1.19	1.23	1.43	1.29	1.56	1.11	1.43	1.85	1.94
b. Highway	364.88	330.31	316.57	309.3	301.39	255.99	280.97	282.65	278.33
c. Railway	0.82	0.65	0.65	0.68	0.65	0.67	1.18	1.15	1.22
d. Marine	1.63	2.11	2.16	2.35	3.25	3.45	3.89	4.25	4.11
4. Other Sectors	**204.04**	**191.08**	**188.68**	**186.34**	**185.53**	**181.4**	**178.54**	**178.91**	**214.92**
a. Residential	180.52	168.57	165.83	163.13	160.59	156.23	151.51	149.46	177.62
b. Agriculture/Forestry/Fishery	23.52	22.51	22.86	23.21	24.94	25.17	27.03	29.44	37.3
Industrial Processes	**456.82**	**396.33**	**443.94**	**496.53**	**489.5**	**613.74**	**762.63**	**781.45**	**768.5**
a. Minerals	410.42	351.87	398.95	451.45	445.45	564.87	712.93	734.03	718.21
b. Chemicals	7.14	6.58	8.49	8.18	7.71	6.64	7.8	7.56	6.54
c. Ore resources	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.02
d. Other production	33.17	31.38	29.47	29.65	29.27	35.26	34.8	32.88	37.12
e. Others	6.06	6.47	7.01	7.24	7.04	6.94	7.09	6.93	6.61
Total	**1,044.83**	**934.60**	**968.22**	**1,012.80**	**998.60**	**1,073.51**	**1,247.89**	**1,271.42**	**1,285.62**

APPENDIX B

CO_2 EMISSION ESTIMATION OF TKI OPERATIONS

Table B.1 CO_2 Emission Estimation of TKI Enterprises

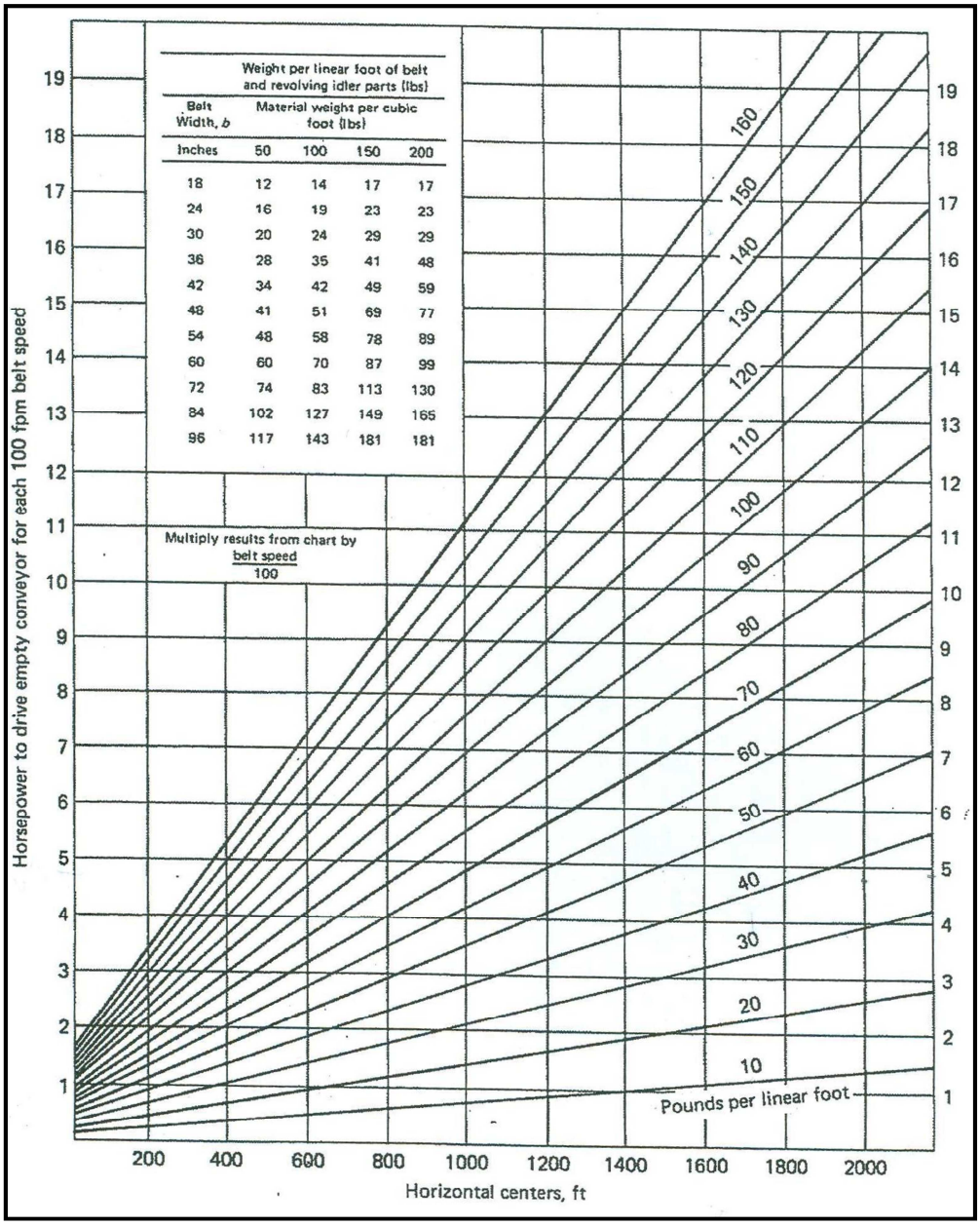
		Unit	Fuel	Ton of Oil Equivalent Factor	TOE	Energy Kcal	Energy Tjoule	Carbon Emission Factor tC/TJ	Carbon Oxidized	Convert to CO_2 emission tones
	Years	Liters	A (tonnes)	B	C=A*B	$D=C*10^7$	$E=D*4.184*10^{-9}$	F	G	J=E*F*G*44/12
ELI	2002	35,555,959	29,511.45	1.02	30,101.67	3.01E+11	1,259.45	20.2	0.99	92,350.73
	2003	35,984,628	29,867.24	1.02	30,464.59	3.05E+11	1,274.64	20.2	0.99	93,464.13
	2004	28,072,834	23,300.45	1.02	23,766.46	2.38E+11	994.39	20.2	0.99	72,914.55
	2005	30,982,847	25,715.76	1.02	26,230.08	2.62E+11	1,097.47	20.2	0.99	80,472.83
	2006	31,084,303	25,799.97	1.02	26,315.97	2.63E+11	1,101.06	20.2	0.99	80,736.34
	2007	28,072,834	23,300.45	1.02	23,766.46	2.38E+11	994.39	20.2	0.99	72,914.55
CLI	2002	6,828,654	5,667.78	1.02	5,781.14	57,811,384,764	241.88	20.2	0.99	17,736.30
	2003	8,066,253	6,694.99	1.02	6,828.89	68,288,897,898	285.72	20.2	0.99	20,950.76
	2004	7,900,197	6,557.16	1.02	6,688.31	66,883,067,802	279.84	20.2	0.99	20,519.46
	2005	7,545,046	6,262.39	1.02	6,387.64	63,876,359,436	267.26	20.2	0.99	19,597.01
	2006	6,372,503	5,289.18	1.02	5,394.96	53,949,610,398	225.73	20.2	0.99	16,551.52
	2007	6,585,271	5,465.77	1.02	5,575.09	55,750,904,286	233.26	20.2	0.99	17,104.15
GLI	2002	14,241,642	11,820.56	1.02	12,056.97	1.21E+11	504.46	20.2	0.99	36,990.31
	2003	13,599,043	11,287.21	1.02	11,512.95	1.15E+11	481.70	20.2	0.99	35,321.27
	2004	14,383,412	11,938.23	1.02	12,177.00	1.22E+11	509.49	20.2	0.99	37,358.54
	2005	14,615,730	12,131.06	1.02	12,373.68	1.24E+11	517.71	20.2	0.99	37,961.94
	2006	12,892,419	10,700.71	1.02	10,914.72	1.09E+11	456.67	20.2	0.99	33,485.93
	2007	12,672,020	10,517.78	1.02	10,728.13	1.07E+11	448.87	20.2	0.99	32,913.48
ILI	2002	259,051	215.01	1.02	219.31	2,193,125,766	9.18	20.2	0.99	672.84
	2003	327,994	272.24	1.02	277.68	2,776,797,204	11.62	20.2	0.99	851.91
	2004	477,291	396.15	1.02	404.07	4,040,745,606	16.91	20.2	0.99	1,239.68
	2005	509,064	422.52	1.02	430.97	4,309,735,824	18.03	20.2	0.99	1,322.21
	2006	440,055	365.25	1.02	372.55	3,725,505,630	15.59	20.2	0.99	1,142.97
	2007	171,205	142.10	1.02	144.94	1,449,421,530	6.06	20.2	0.99	444.68

Table B.1 CO_2 Emission Estimation of TKI Enterprises (cont'd)

		Unit	Fuel	Ton of Oil Equivalent Factor	TOE	Energy Kcal	Energy Tjoule	Carbon Emission Factor tC/TJ	Carbon Oxidized	Convert to CO_2 emission tones
	Years	Liters	A (tonnes)	B	C=A*B	$D=C*10^7$	$E=D*4.184*10^{-9}$	F	G	J=E*F*G*44/12
SLI	2002	6,527,110	5,417.50	1.02	5,525.85	55,258,513,260	231.20	20.2	0.99	16,953.09
	2003	6,422,742	5,330.88	1.02	5,437.49	54,374,933,772	227.50	20.2	0.99	16,682.01
	2004	6,074,911	5,042.18	1.02	5,143.02	51,430,196,526	215.18	20.2	0.99	15,778.58
	2005	5,873,992	4,875.41	1.02	4,972.92	49,729,216,272	208.07	20.2	0.99	15,256.72
	2006	6,867,596	5,700.10	1.02	5,814.11	58,141,067,736	243.26	20.2	0.99	17,837.45
	2007	7,032,897	5,837.30	1.02	5,954.05	59,540,506,002	249.12	20.2	0.99	18,266.79
BLI	2002	6,371,702	5,288.51	1.02	5,394.28	53,942,829,132	225.70	20.2	0.99	16,549.44
	2003	5,585,487	4,635.95	1.02	4,728.67	47,286,732,942	197.85	20.2	0.99	14,507.38
	2004	4,231,151	3,511.86	1.02	3,582.09	35,820,924,366	149.87	20.2	0.99	10,989.72
	2005	6,170,670	5,121.66	1.02	5,224.09	52,240,892,220	218.58	20.2	0.99	16,027.30
	2006	5,751,101	4,773.41	1.02	4,868.88	48,688,821,066	203.71	20.2	0.99	14,937.53
	2007	5,466,416	4,537.13	1.02	4,627.87	46,278,677,856	193.63	20.2	0.99	14,198.11
GELI	2002	10,924,758	9,067.55	1.02	9,248.90	92,489,001,228	386.97	20.2	0.99	28,375.25
	2003	8,347,219	6,928.19	1.02	7,066.76	70,667,556,054	295.67	20.2	0.99	21,680.52
	2004	7,845,361	6,511.65	1.02	6,641.88	66,418,826,226	277.90	20.2	0.99	20,377.03
	2005	8,601,789	7,139.48	1.02	7,282.27	72,822,745,674	304.69	20.2	0.99	22,341.73
	2006	7,532,878	6,252.29	1.02	6,377.33	63,773,345,148	266.83	20.2	0.99	19,565.41
	2007	8,016,944	6,654.06	1.02	6,787.14	67,871,447,904	283.97	20.2	0.99	20,822.69
YLI	2002	6,281,313	5,213.49	1.02	5,317.76	53,177,595,858	222.50	20.2	0.99	16,314.67
	2003	5,545,344	4,602.64	1.02	4,694.69	46,946,882,304	196.43	20.2	0.99	14,403.11
	2004	5,050,033	4,191.53	1.02	4,275.36	42,753,579,378	178.88	20.2	0.99	13,116.63
	2005	4,040,465	3,353.59	1.02	3,420.66	34,206,576,690	143.12	20.2	0.99	10,494.44
	2006	5,399,131	4,481.28	1.02	4,570.90	45,709,043,046	191.25	20.2	0.99	14,023.35
	2007	5,155,547	4,279.10	1.02	4,364.69	43,646,860,902	182.62	20.2	0.99	13,390.68

APPENDIX C

POWER RATING CHARTS OF BELT CONVEYOR



Belt Width, b	Weight per linear foot of belt and revolving idler parts (lbs) — Material weight per cubic foot (lbs)			
Inches	50	100	150	200
18	12	14	17	17
24	16	19	23	23
30	20	24	29	29
36	28	35	41	48
42	34	42	49	59
48	41	51	69	77
54	48	58	78	89
60	60	70	87	99
72	74	83	113	130
84	102	127	149	165
96	117	143	181	181

Figure C.1 Horsepower required to drive empty conveyor (CEMA, 1997)

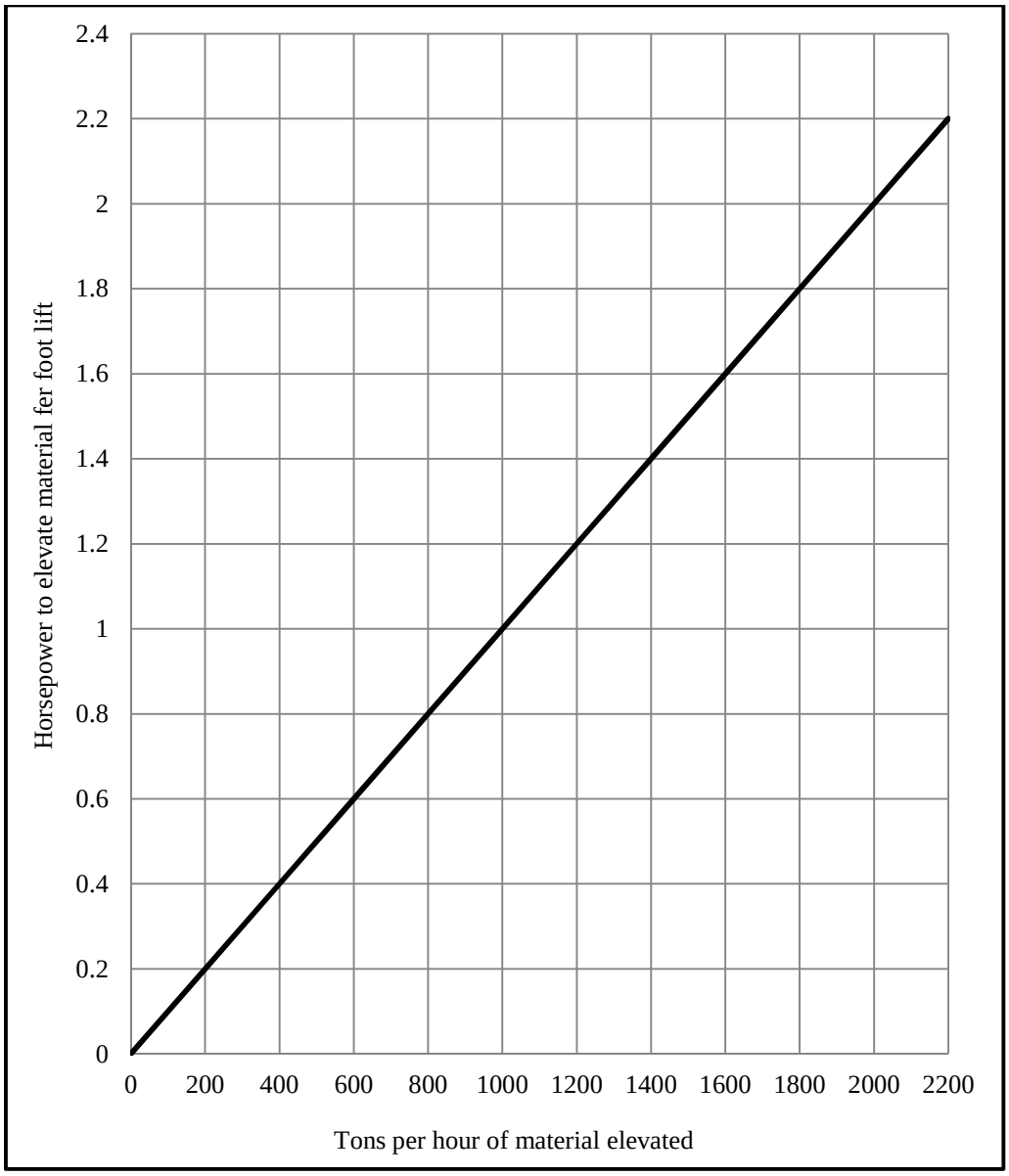


Figure C.2 Horsepower required to elevate material (CEMA, 1997)

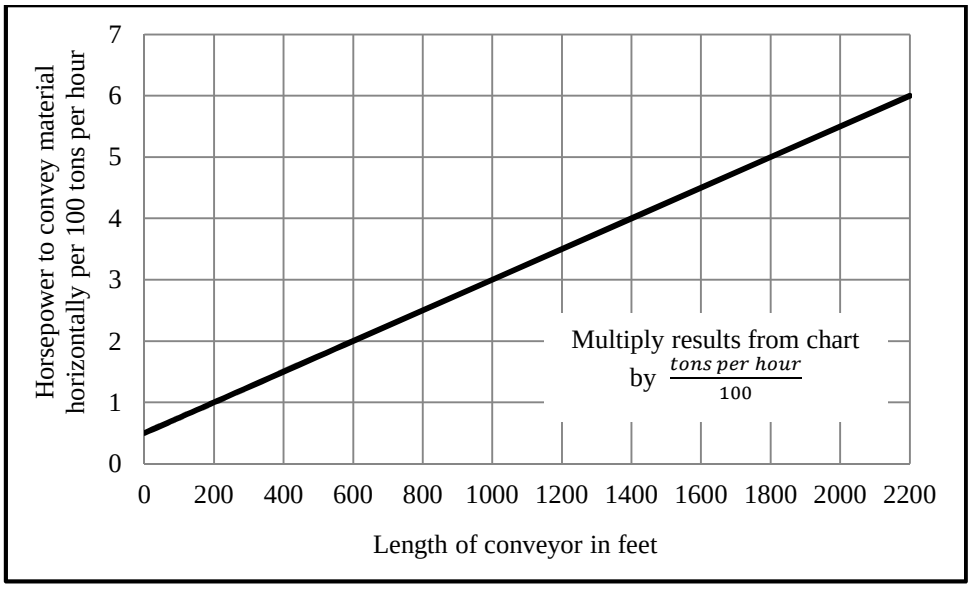
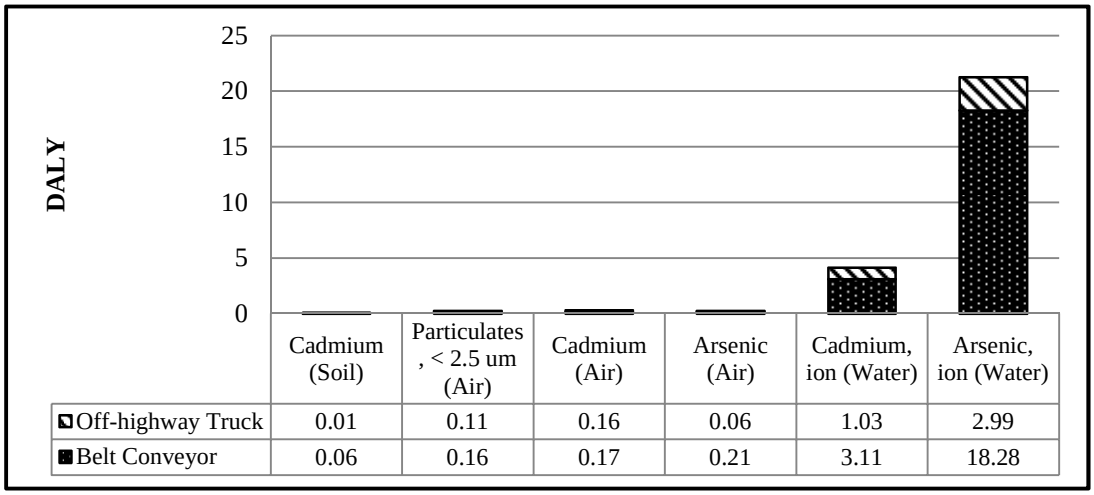


Figure C.3 Horsepower required conveying material horizontally (CEMA, 1997)

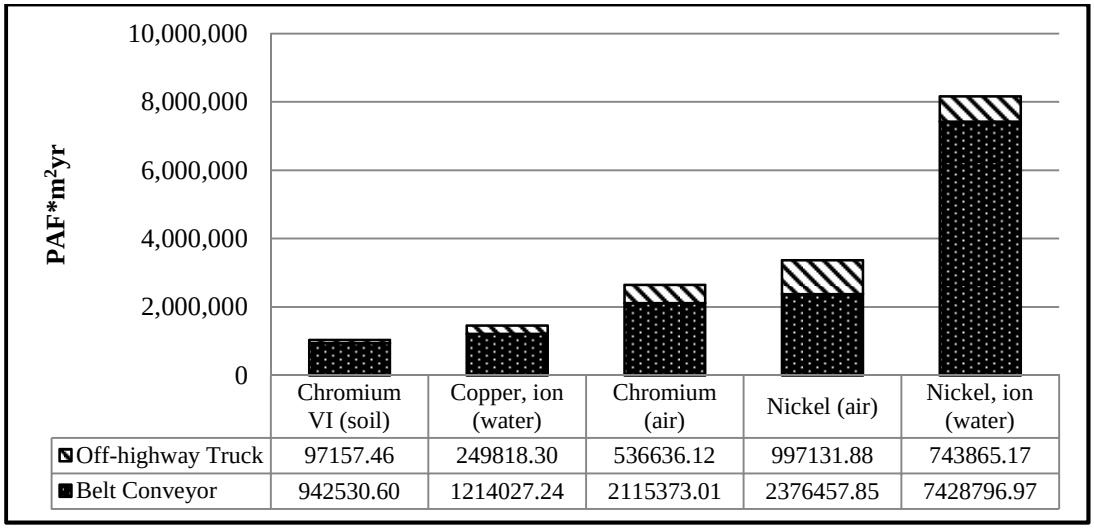
APPENDIX D

COMPARISON OF RESULTS ECO-INDICATOR IMPACT CATEGORIES



	Cadmium (Soil)	Particulates , < 2.5 um (Air)	Cadmium (Air)	Arsenic (Air)	Cadmium, ion (Water)	Arsenic, ion (Water)
Off-highway Truck	0.01	0.11	0.16	0.06	1.03	2.99
Belt Conveyor	0.06	0.16	0.17	0.21	3.11	18.28

Figure D.1 Comparison of off-highway trucks and belt conveyors in carcinogens category



	Chromium VI (soil)	Copper, ion (water)	Chromium (air)	Nickel (air)	Nickel, ion (water)
Off-highway Truck	97157.46	249818.30	536636.12	997131.88	743865.17
Belt Conveyor	942530.60	1214027.24	2115373.01	2376457.85	7428796.97

Figure D.2 Comparison of off-highway trucks and belt conveyors in ecotoxicity category

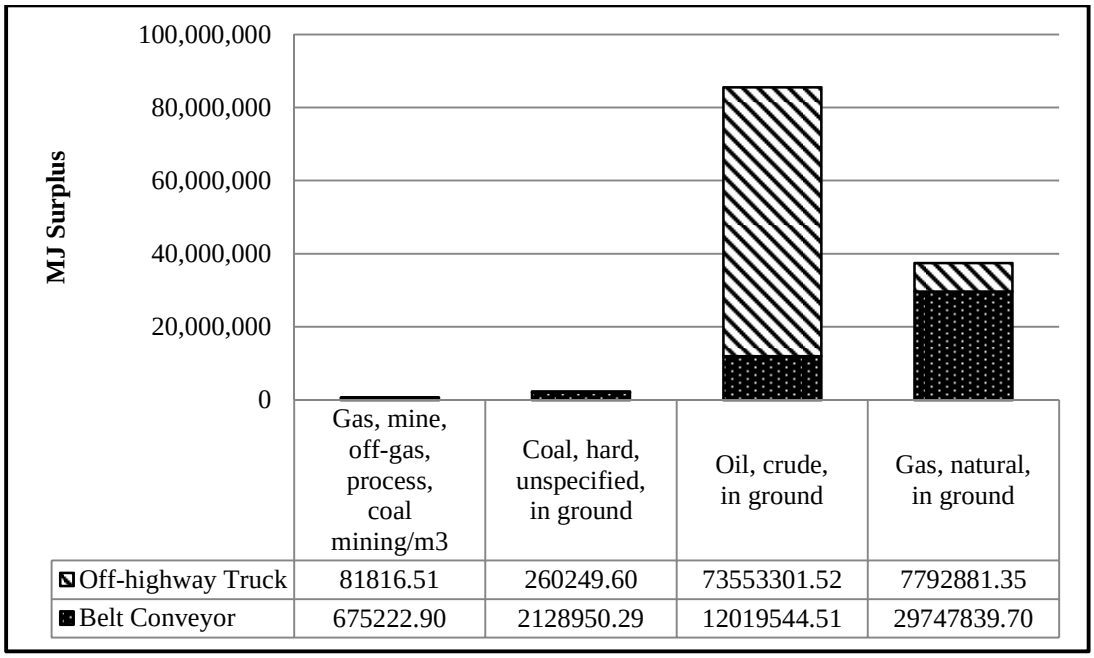


Figure D.3 Comparison of off-highway trucks and belt conveyors in fossil fuels category

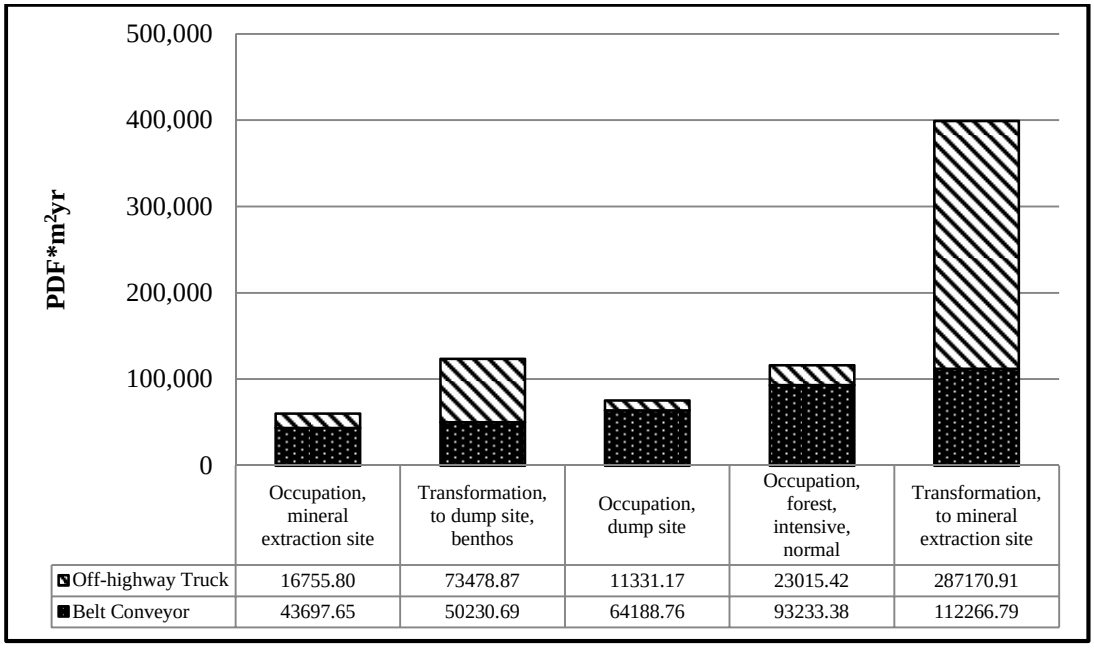


Figure D.4 Comparison of off-highway trucks and belt conveyors in land-use category

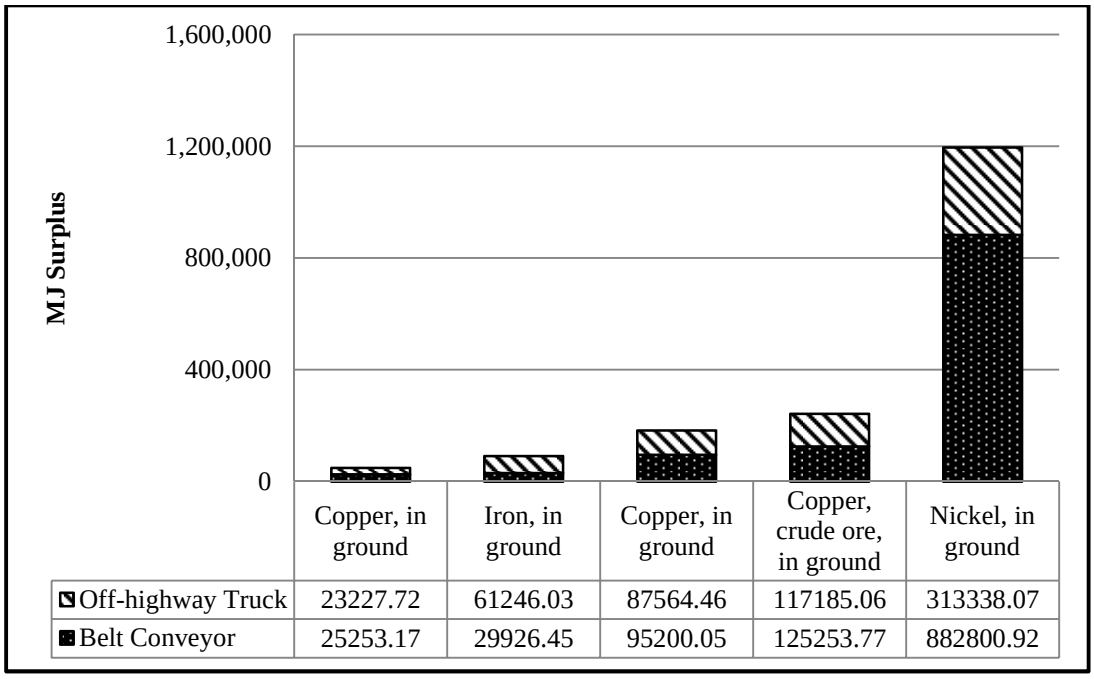


Figure D.5 Comparison of off-highway trucks and belt conveyors in minerals category

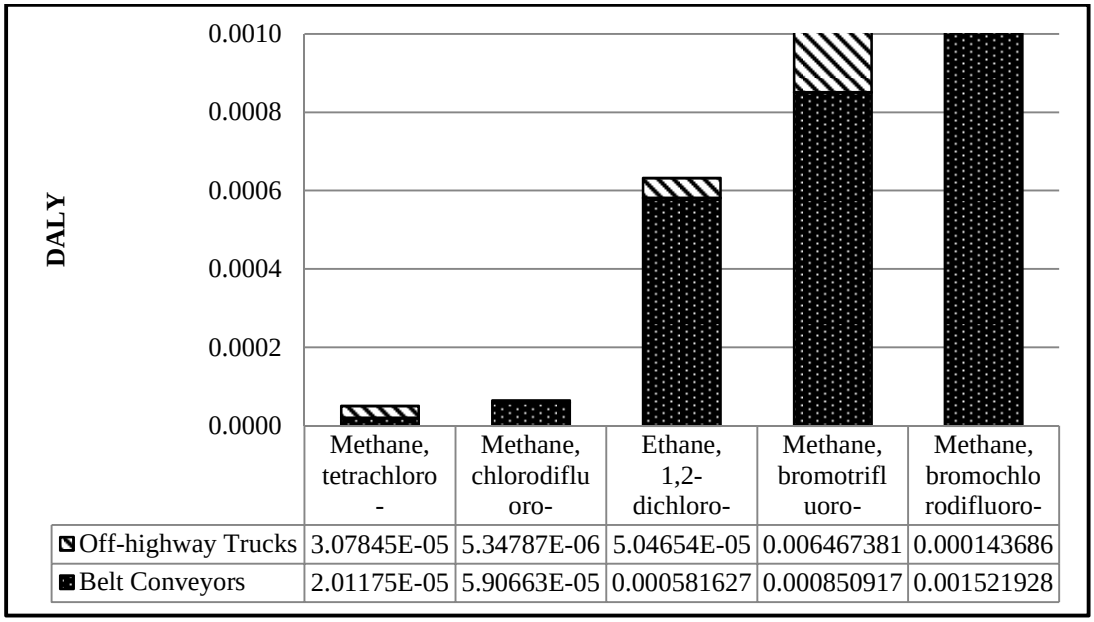
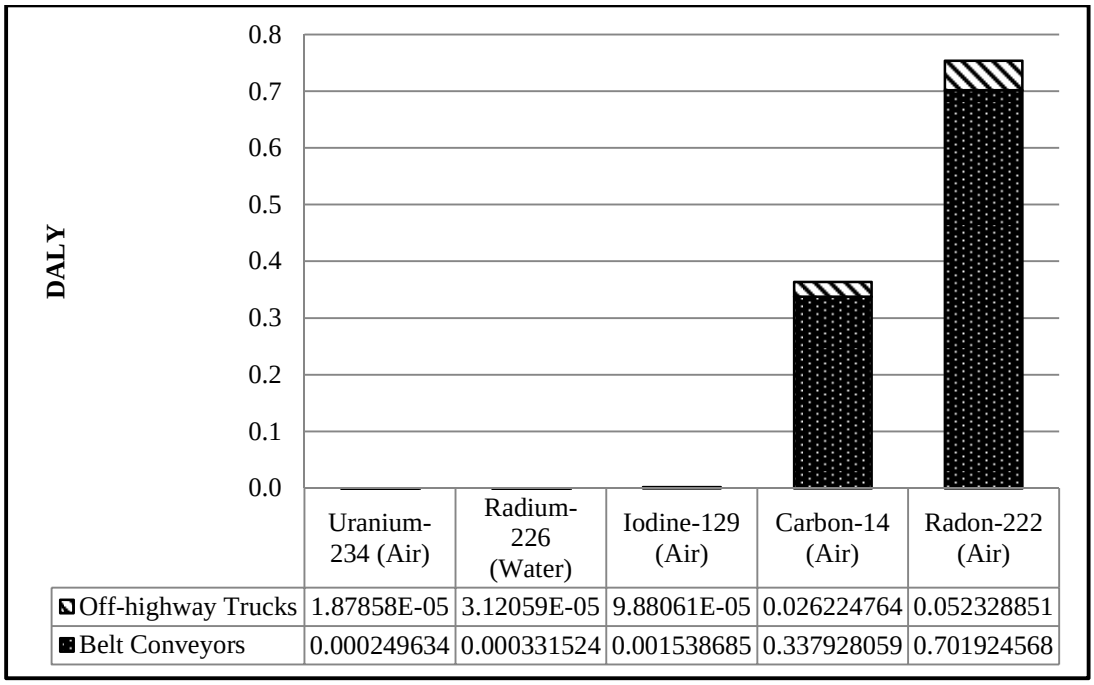
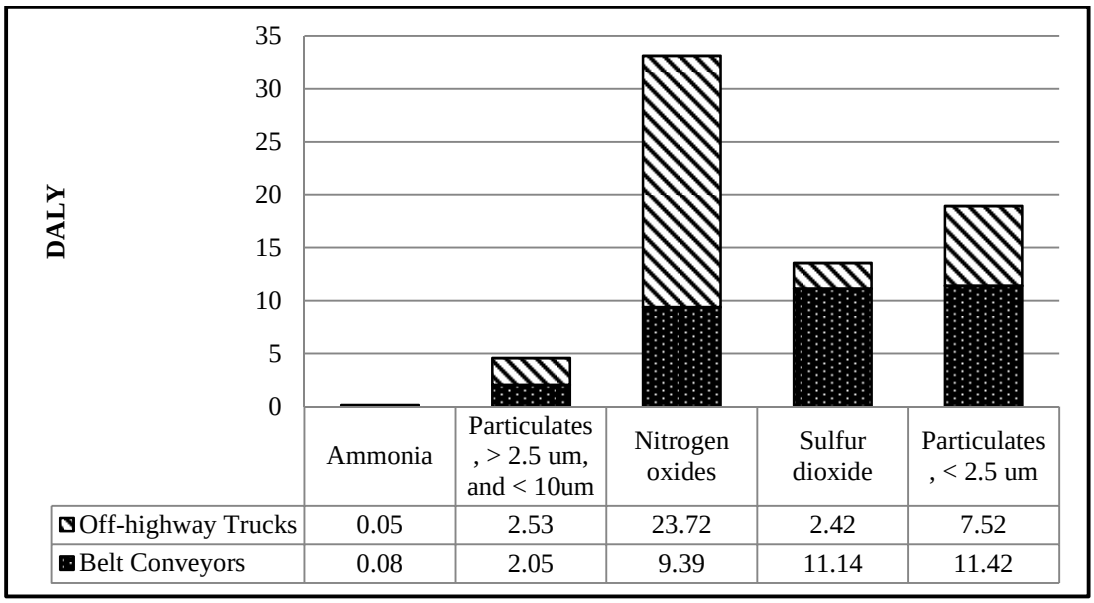


Figure D.6 Comparison of off-highway trucks and belt conveyors in ozone layer category



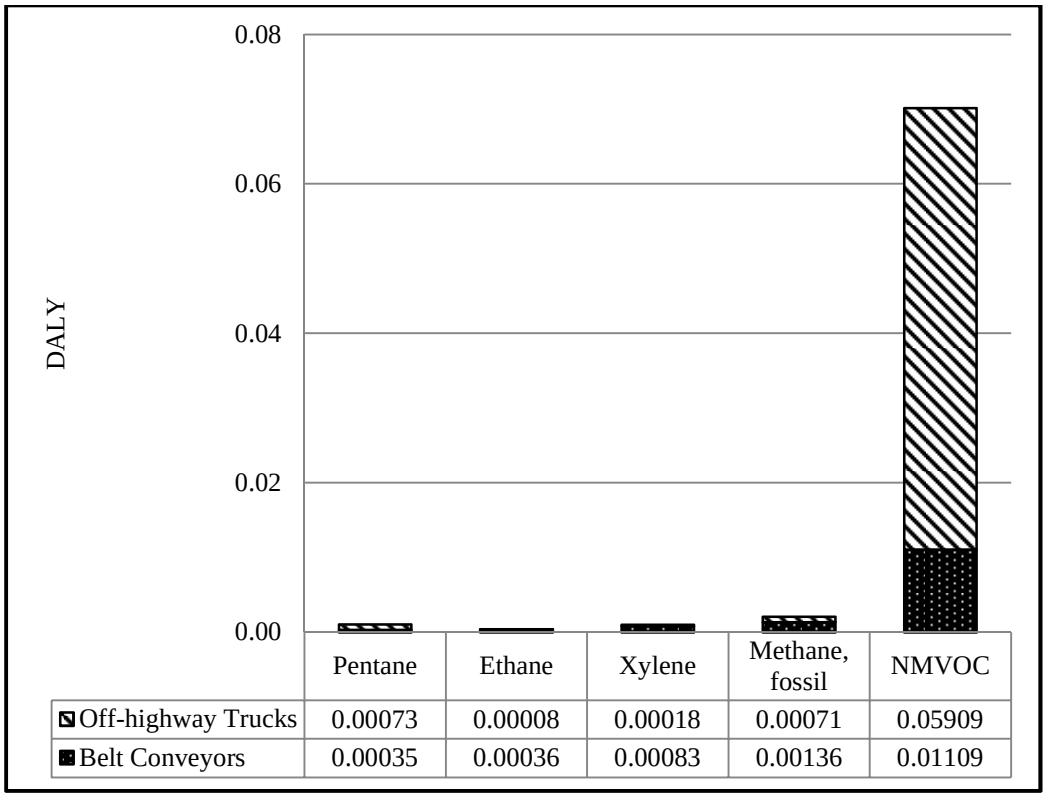
	Uranium-234 (Air)	Radium-226 (Water)	Iodine-129 (Air)	Carbon-14 (Air)	Radon-222 (Air)
Off-highway Trucks	1.87858E-05	3.12059E-05	9.88061E-05	0.026224764	0.052328851
Belt Conveyors	0.000249634	0.000331524	0.001538685	0.337928059	0.701924568

Figure D.7 Comparison of off-highway trucks and belt conveyors in radiation category



	Ammonia	Particulates, > 2.5 um, and < 10um	Nitrogen oxides	Sulfur dioxide	Particulates, < 2.5 um
Off-highway Trucks	0.05	2.53	23.72	2.42	7.52
Belt Conveyors	0.08	2.05	9.39	11.14	11.42

Figure D.8 Comparison of off-highway trucks and belt conveyors in respiratory inorganic category



	Pentane	Ethane	Xylene	Methane, fossil	NMVOC
Off-highway Trucks	0.00073	0.00008	0.00018	0.00071	0.05909
Belt Conveyors	0.00035	0.00036	0.00083	0.00136	0.01109

Figure D.9 Comparison of off-highway trucks and belt conveyors in respiratory organic

APPENDIX E

SIMAPRO MODELS OF MATERIAL HANDLING SYSTEMS

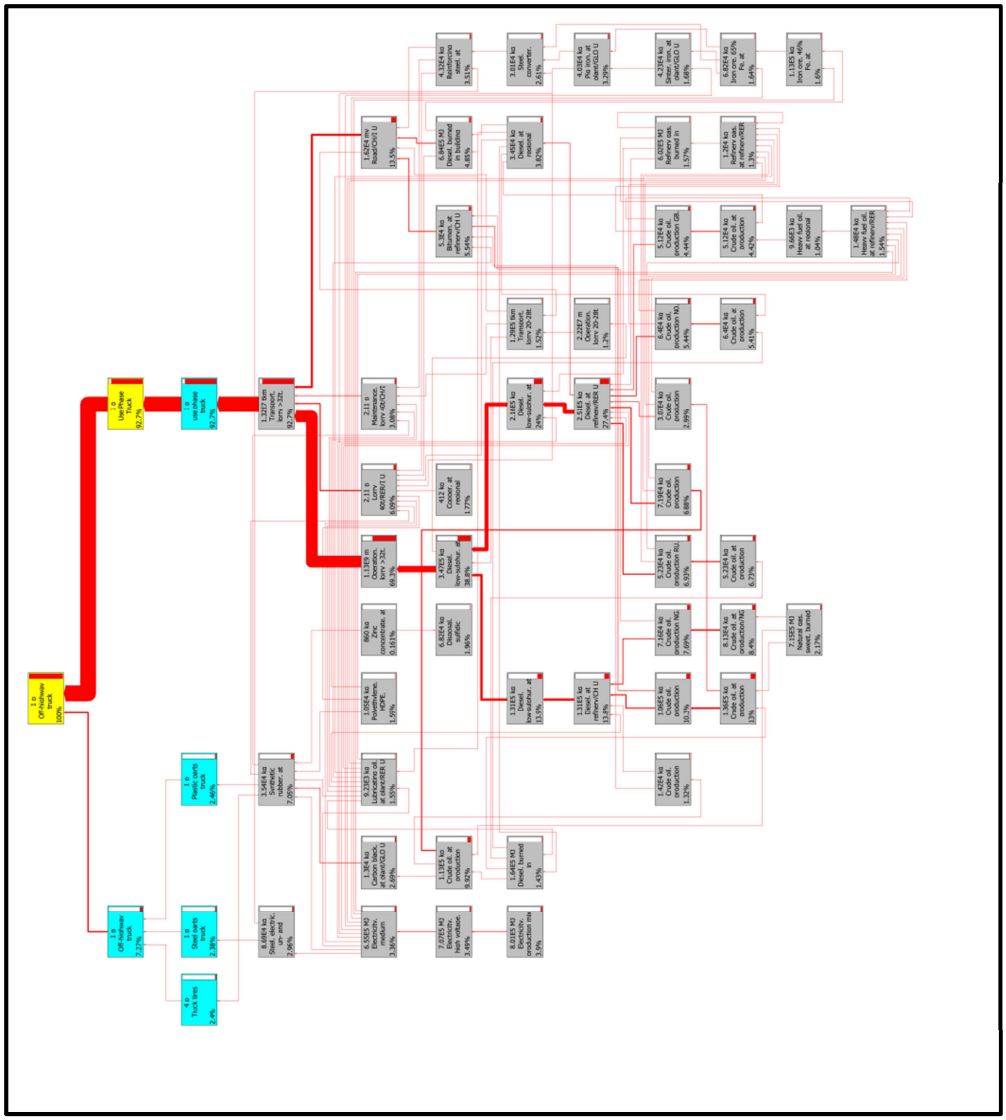


Figure E.1 SIMAPRO model of off-highway truck

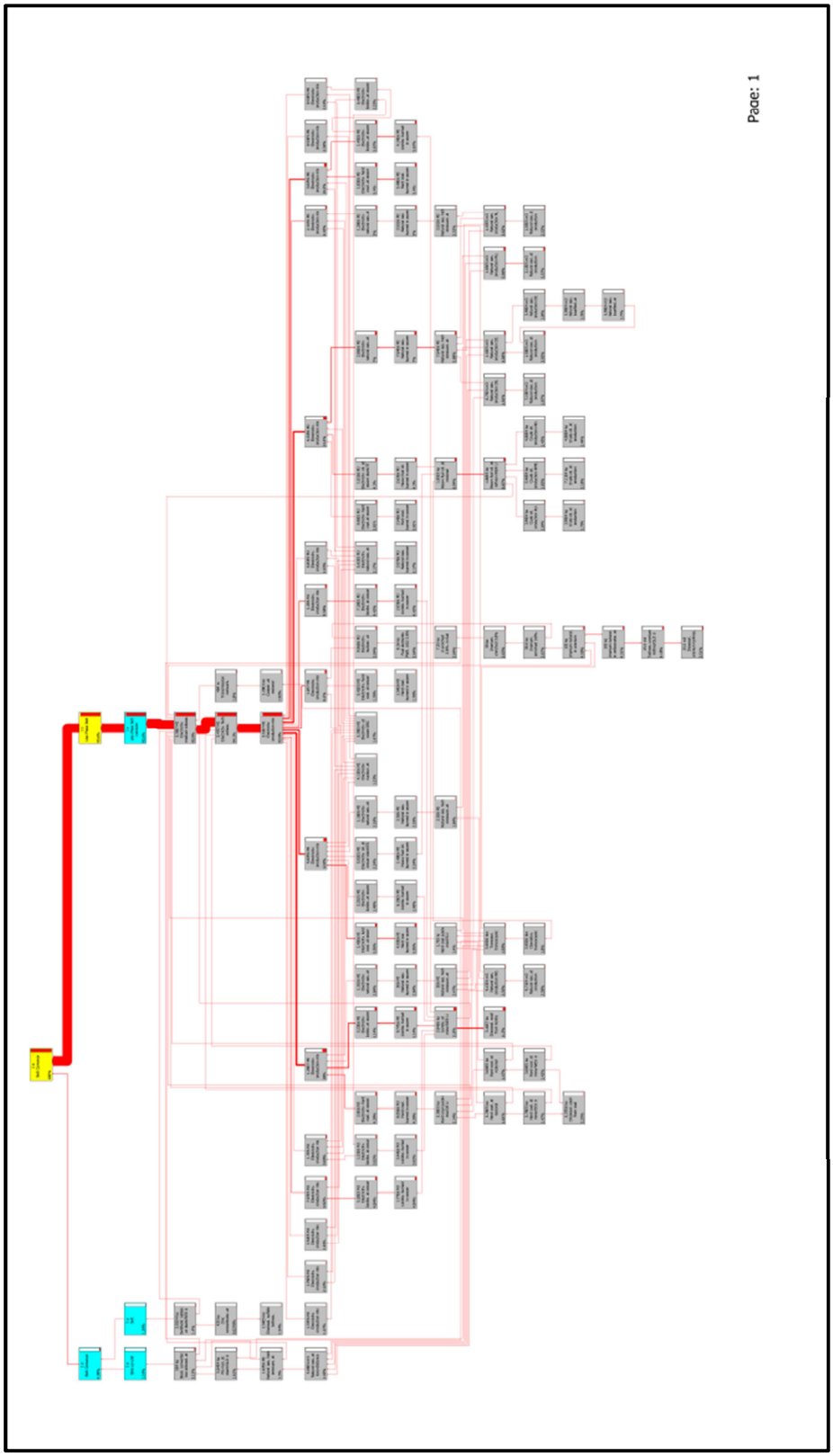
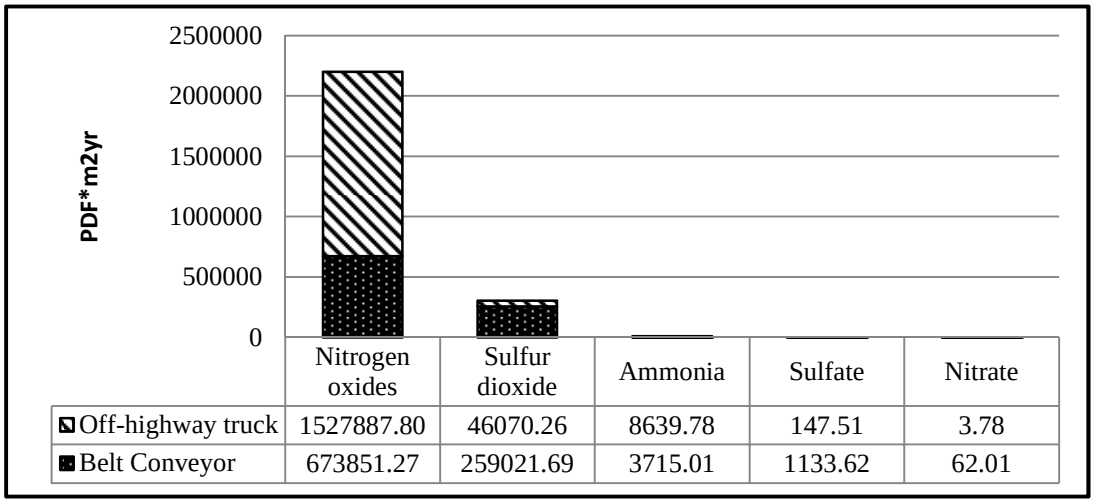


Figure E.2 SIMAPRO model of belt conveyor

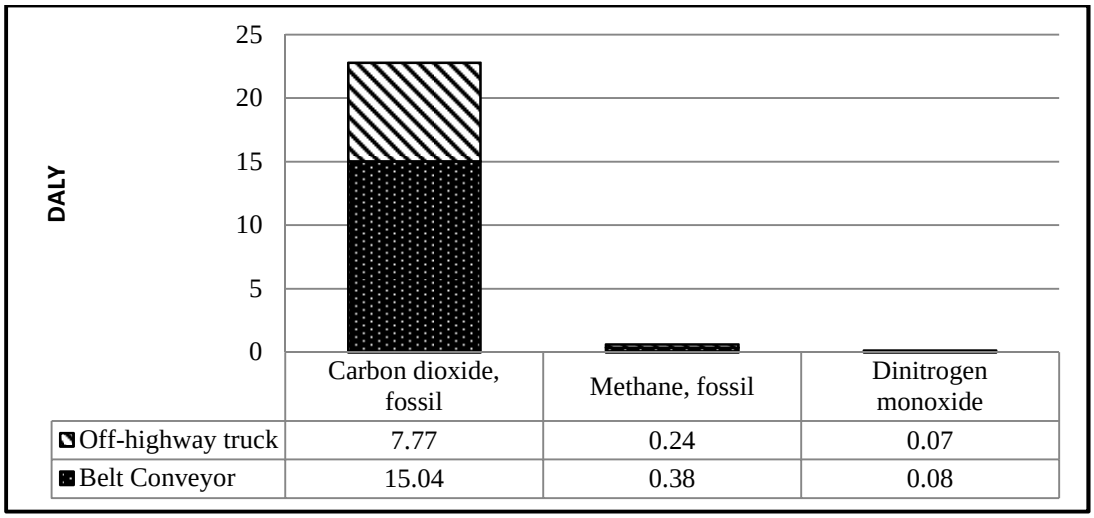
APPENDIX F

COMPARISON OF RESULTS ECO-INDICATOR IMPACT CATEGORIES FOR EASTERN EUROPEAN COUNTRIES



	Nitrogen oxides	Sulfur dioxide	Ammonia	Sulfate	Nitrate
Off-highway truck	1527887.80	46070.26	8639.78	147.51	3.78
Belt Conveyor	673851.27	259021.69	3715.01	1133.62	62.01

Figure F.1 LCA comparison off-highway truck vs. belt conveyor in terms of acidification for Bulgaria



	Carbon dioxide, fossil	Methane, fossil	Dinitrogen monoxide
Off-highway truck	7.77	0.24	0.07
Belt Conveyor	15.04	0.38	0.08

Figure F.2 LCA comparison off-highway truck vs. belt conveyor in terms of climate change for Bulgaria

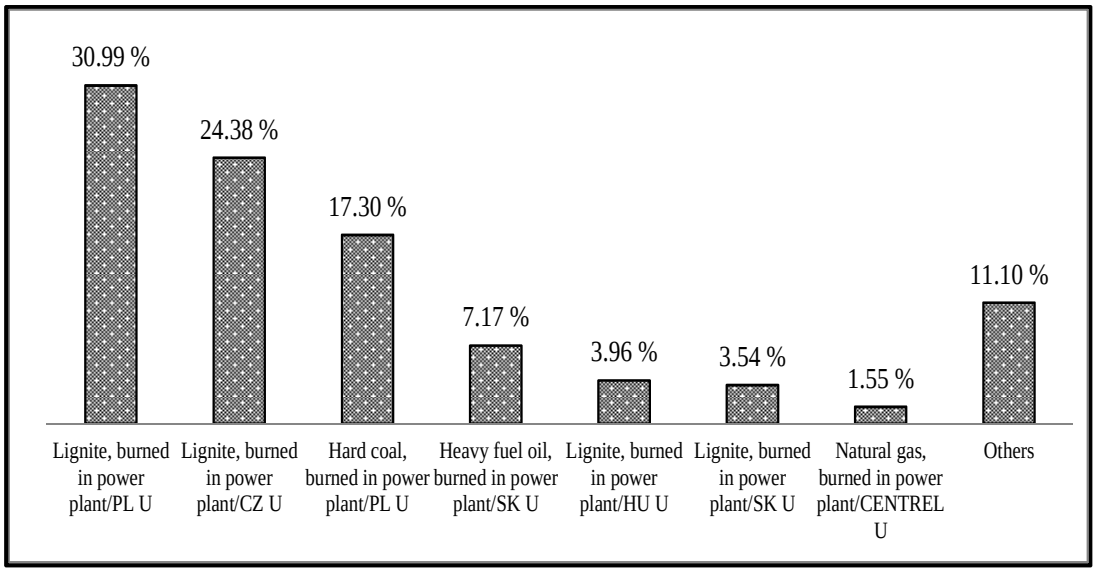


Figure F.3 Process contributions for belt conveyors in acidification category for Bulgaria

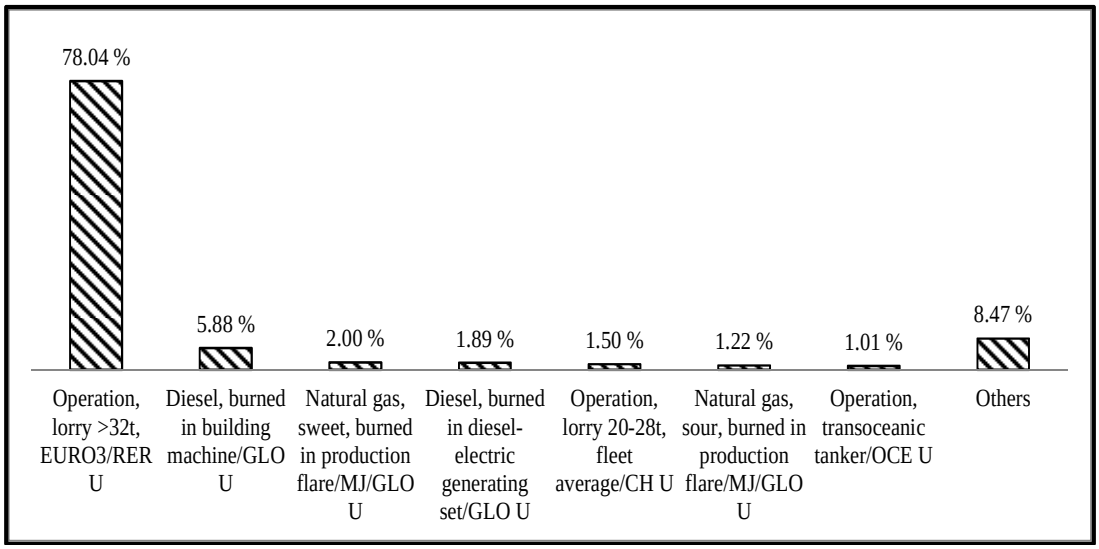


Figure F.4 Process contributions for off-highway truck in acidification category for Bulgaria

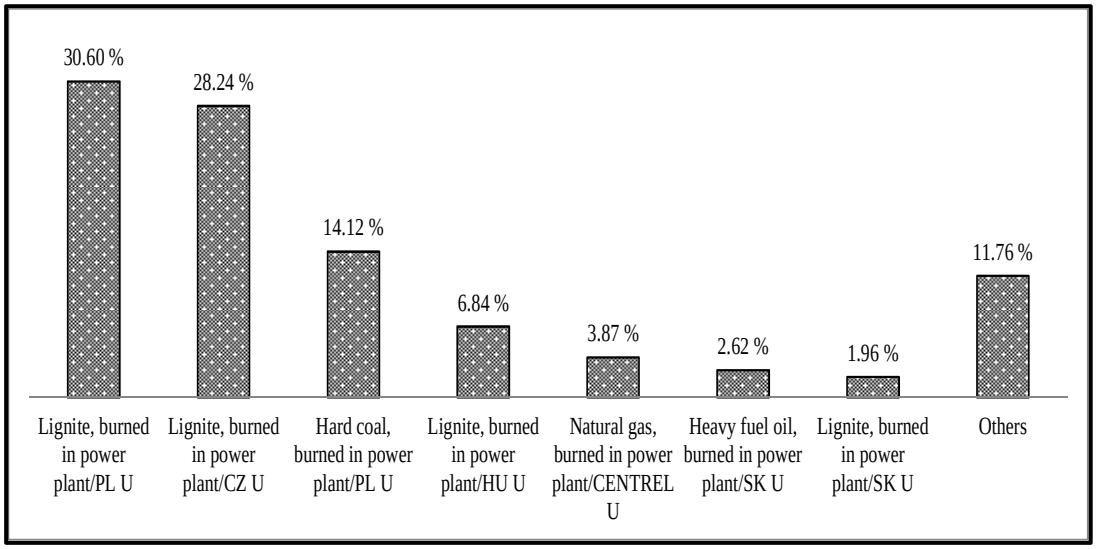


Figure F.5 Process contributions for belt conveyors in climate change category for Bulgaria

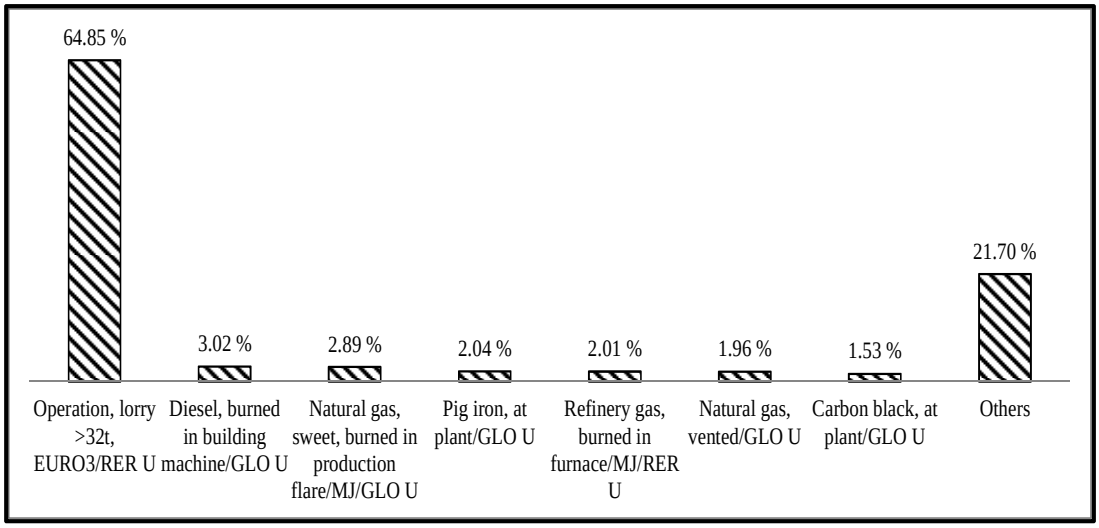


Figure F.6 Process contributions for off-highway truck in climate change category for Bulgaria

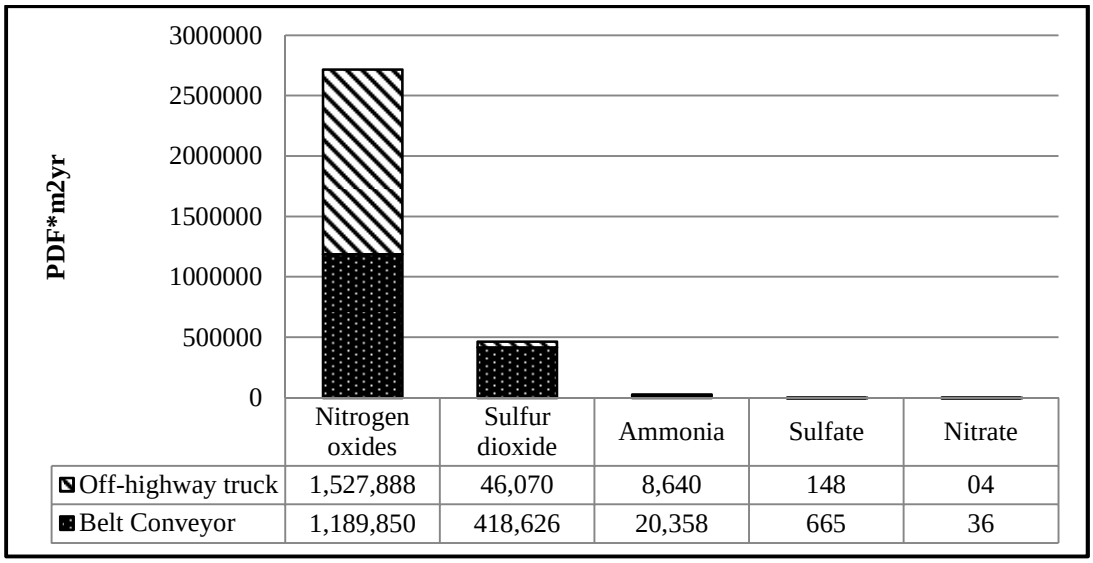


Figure F.7 LCA comparison off-highway truck vs. belt conveyor in terms of acidification for Estonia

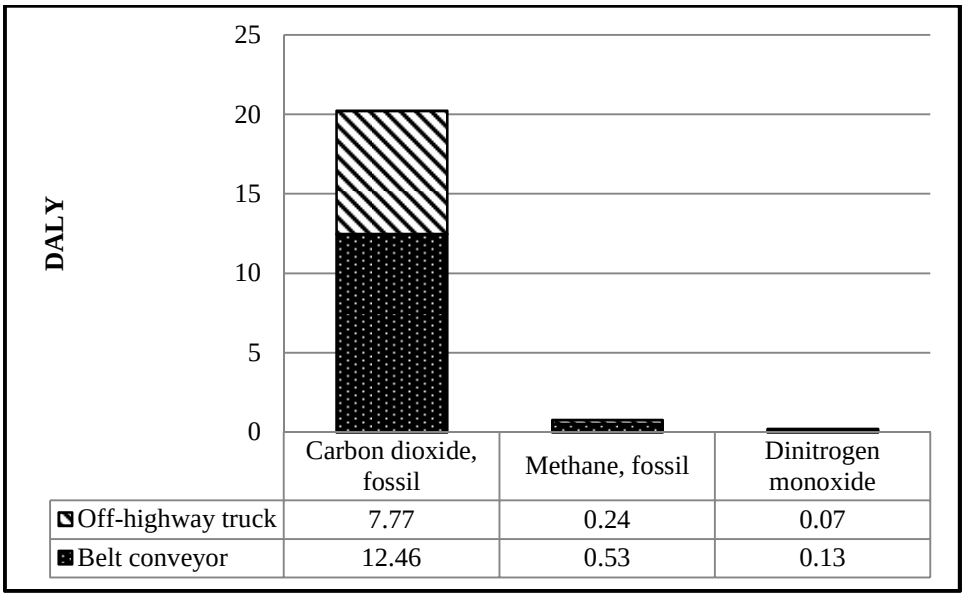


Figure F.8 LCA comparison off-highway truck vs. belt conveyor in terms of climate change for Estonia

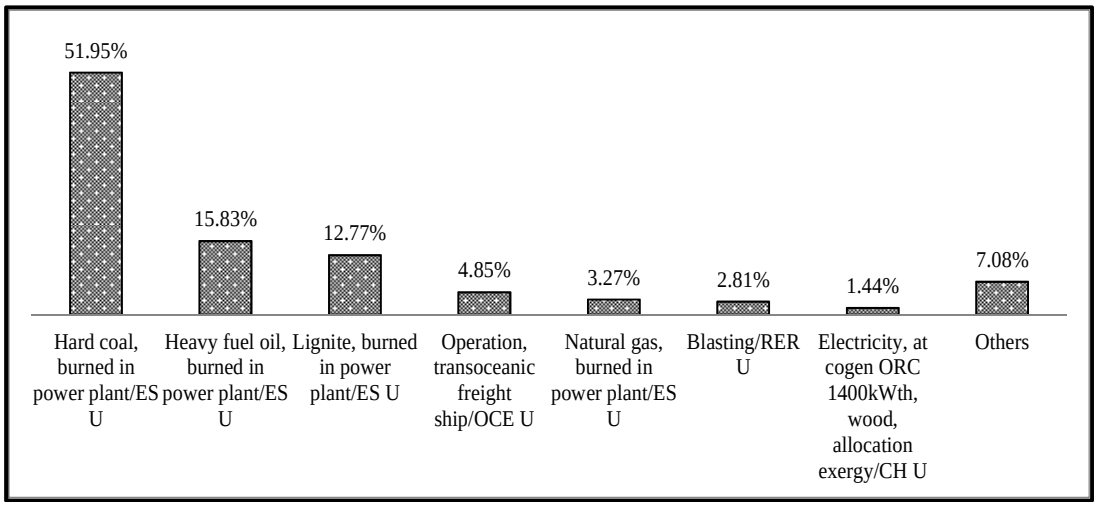


Figure F.9 Process contributions for belt conveyors in acidification category for Estonia

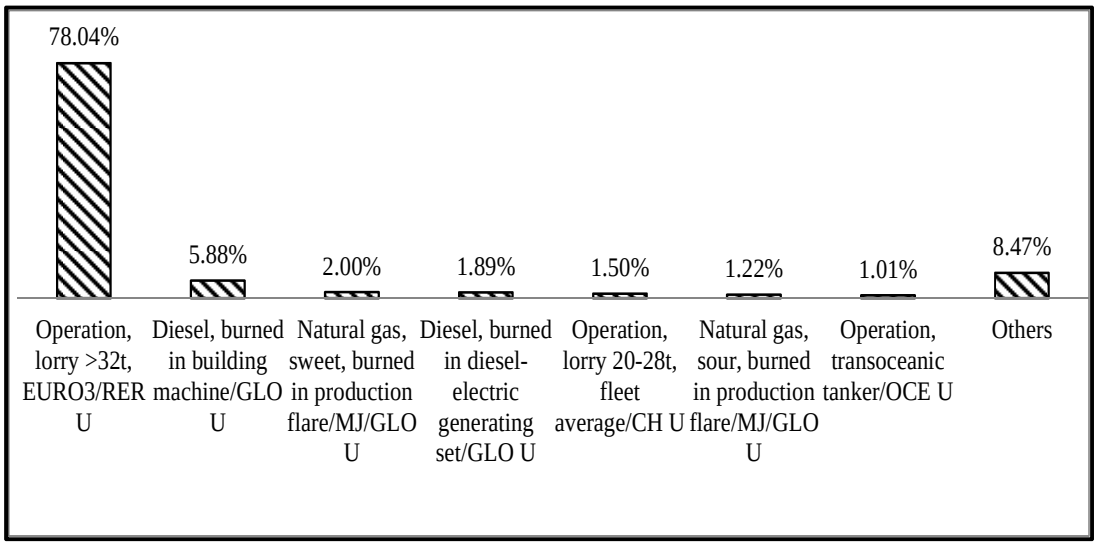


Figure F.10 Process contributions for off-highway truck in acidification category for Estonia

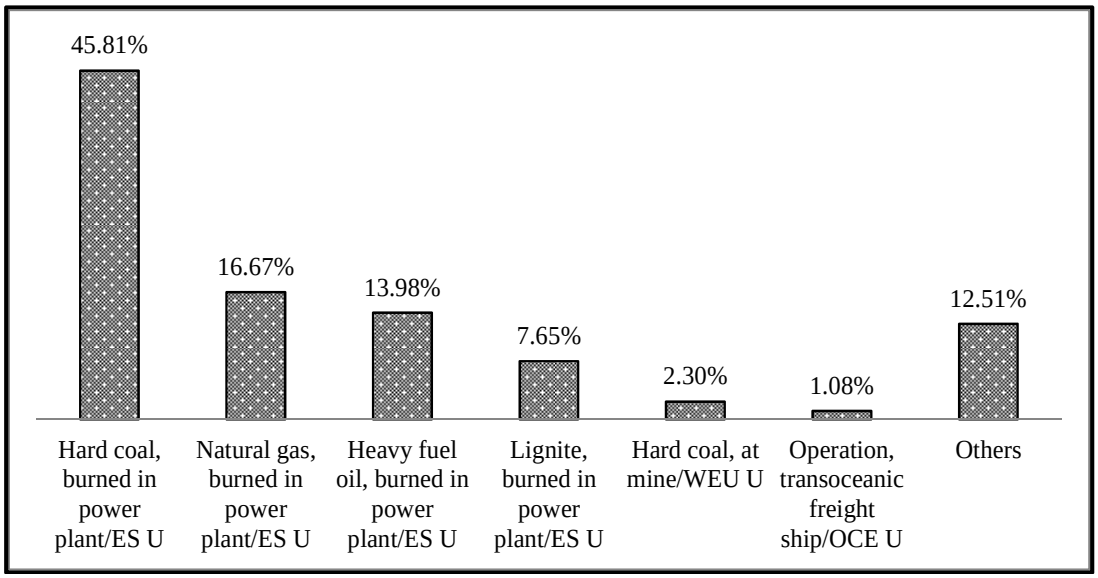


Figure F.11 Process contributions for belt conveyors in climate change category for Estonia

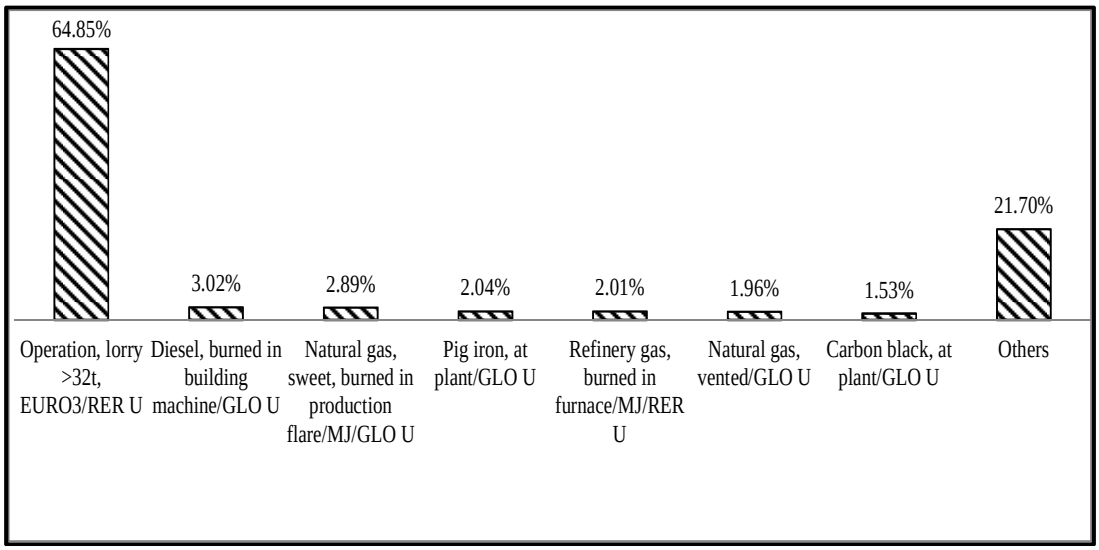


Figure F.12 Process contributions for off-highway truck in climate change category for Estonia

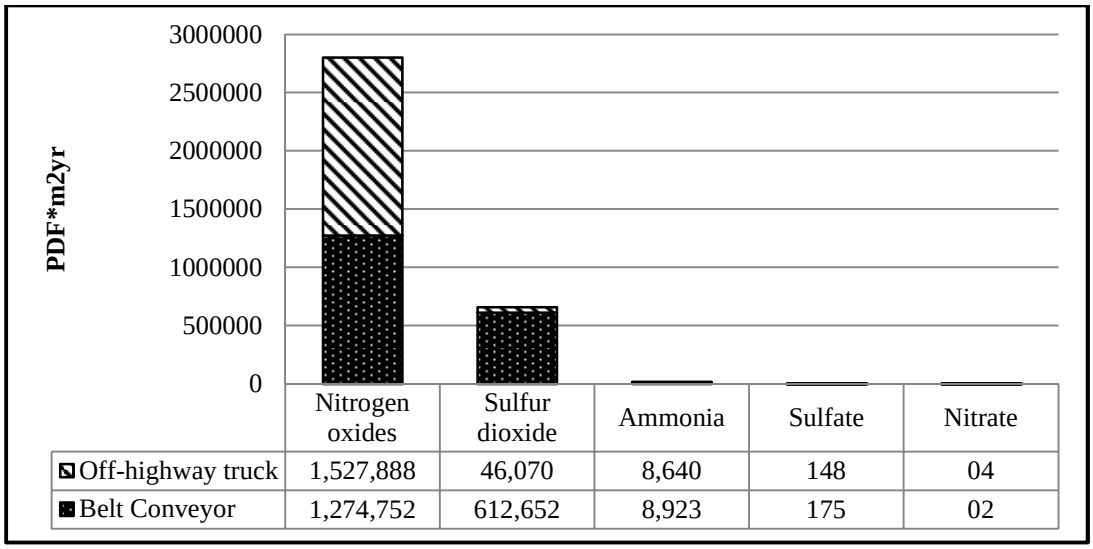


Figure F.13 LCA comparison off-highway truck vs. belt conveyor in terms of acidification for Poland

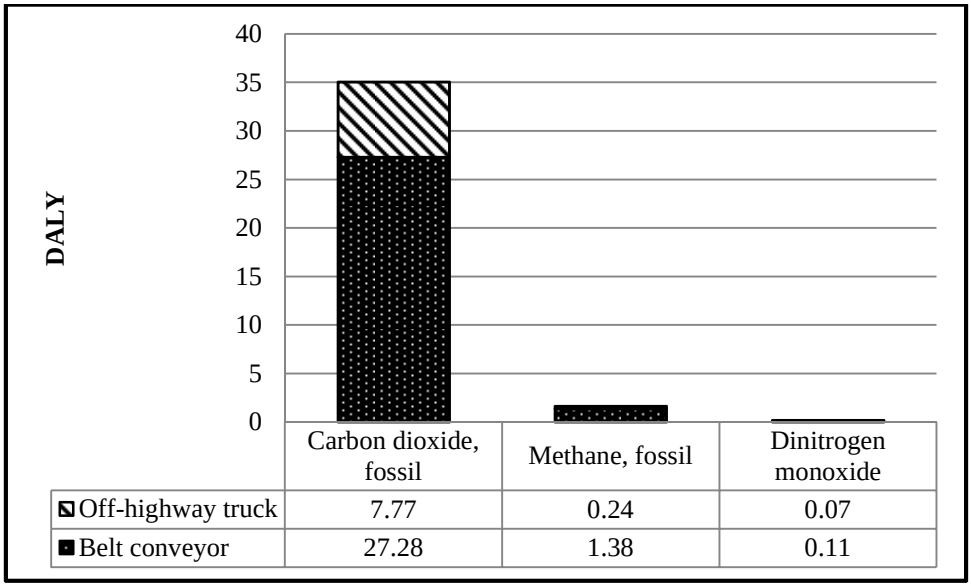


Figure F.14 LCA comparison off-highway truck vs. belt conveyor in terms of climate change for Poland

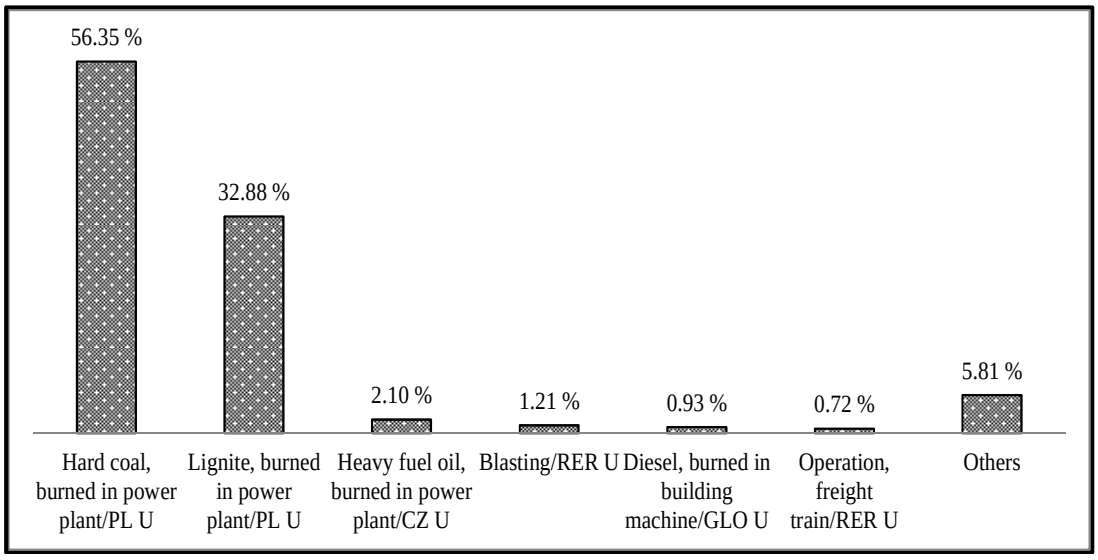


Figure F.15 Process contributions for belt conveyors in acidification category for Poland

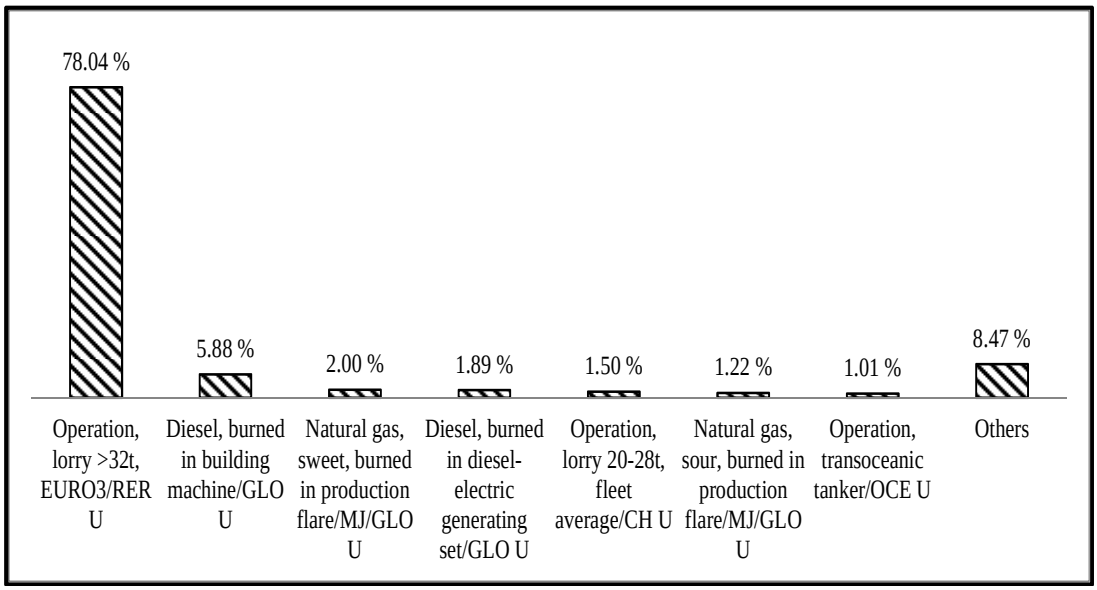


Figure F.16 Process contributions for off-highway truck in acidification category for Poland

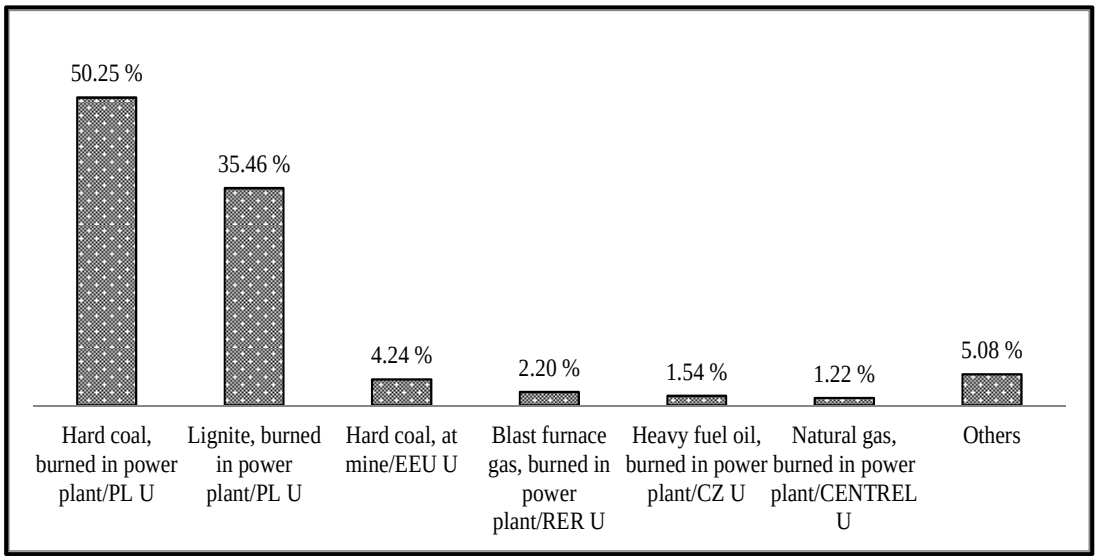


Figure F.17 Process contributions for belt conveyors in climate change category for Poland

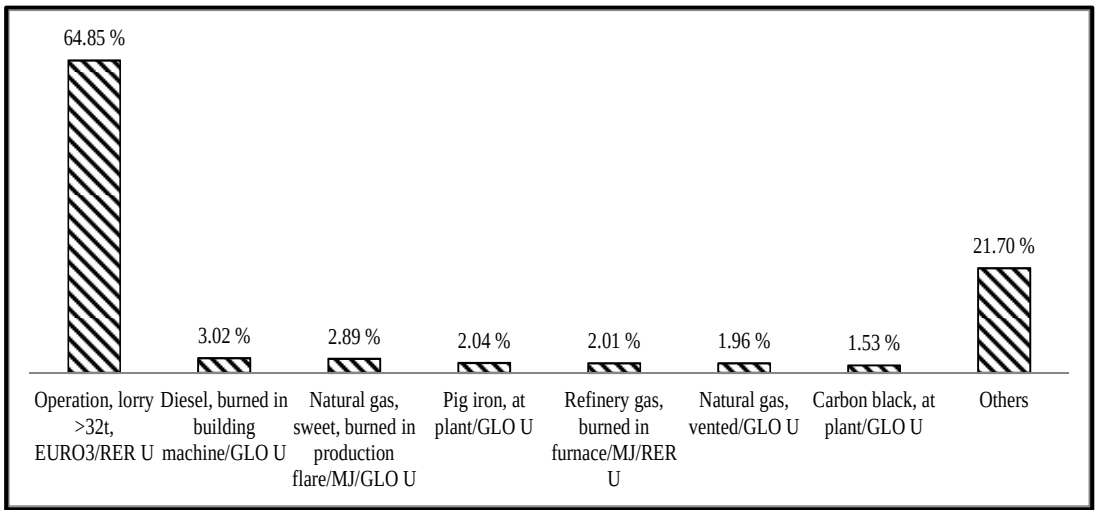


Figure F.18 Process contributions for off-highway truck in climate change category for Poland

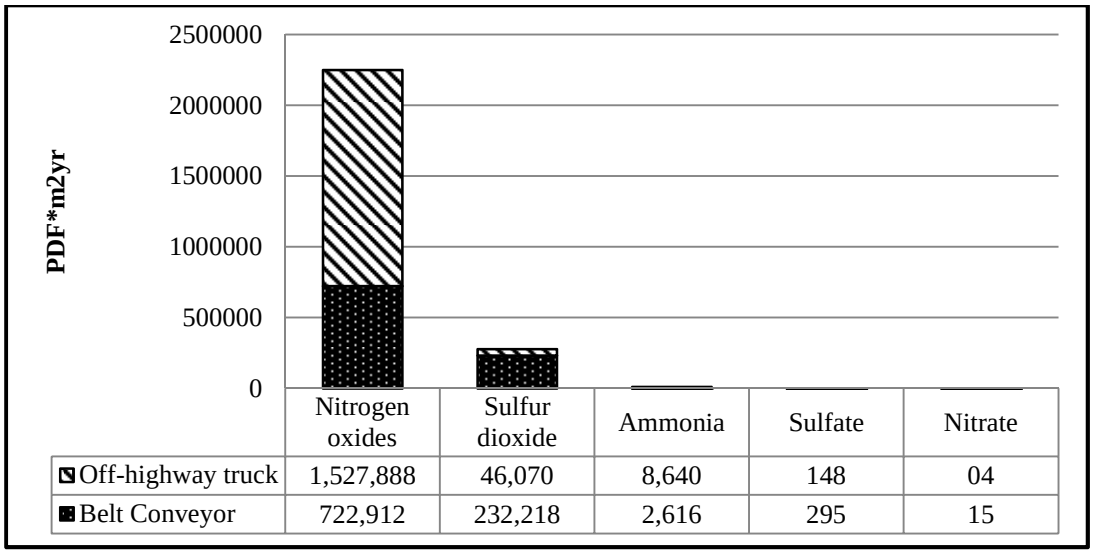


Figure F.19 LCA comparison off-highway truck vs. belt conveyor in terms of acidification for Romania

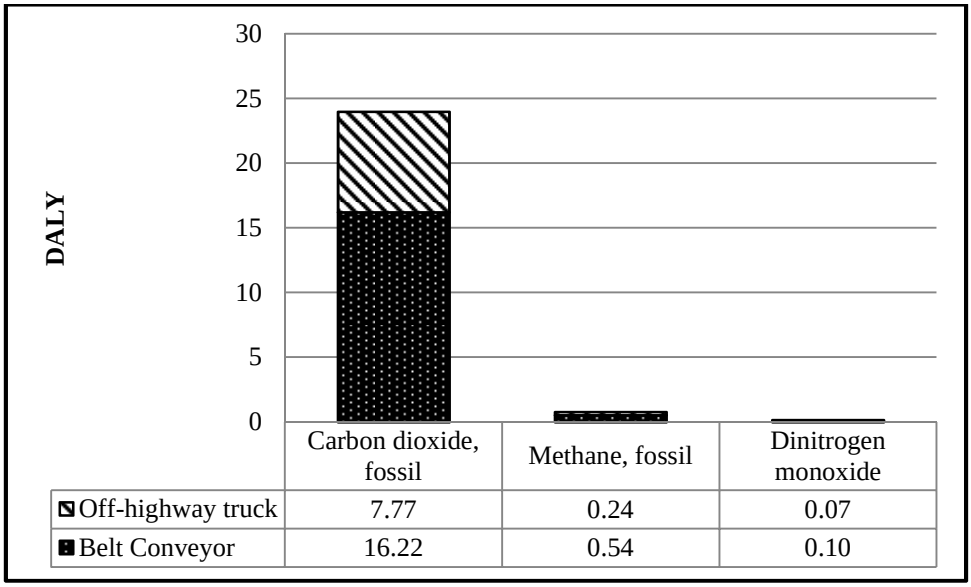


Figure F.20 LCA comparison off-highway truck vs. belt conveyor in terms of climate change for Romania

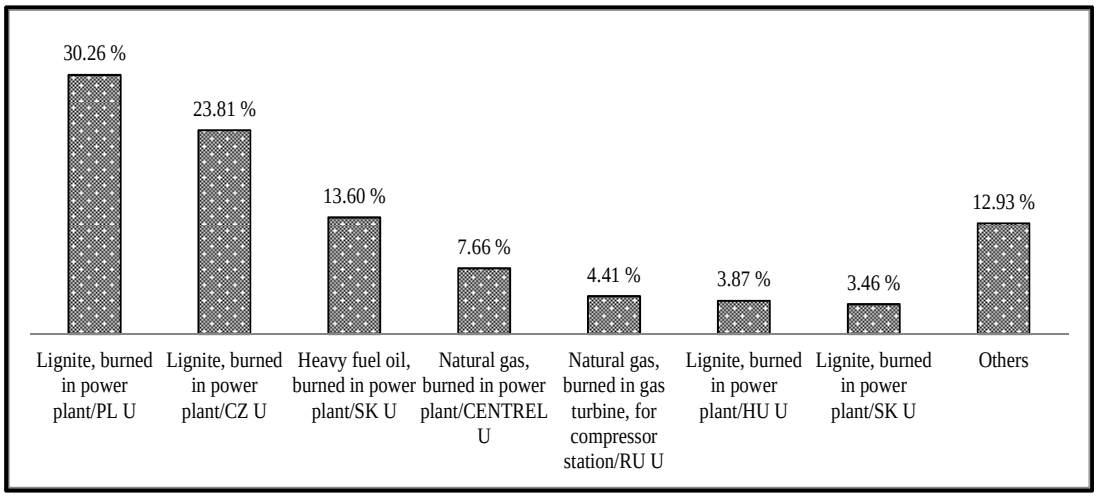


Figure F.21 Process contributions for belt conveyors in acidification category for Romania

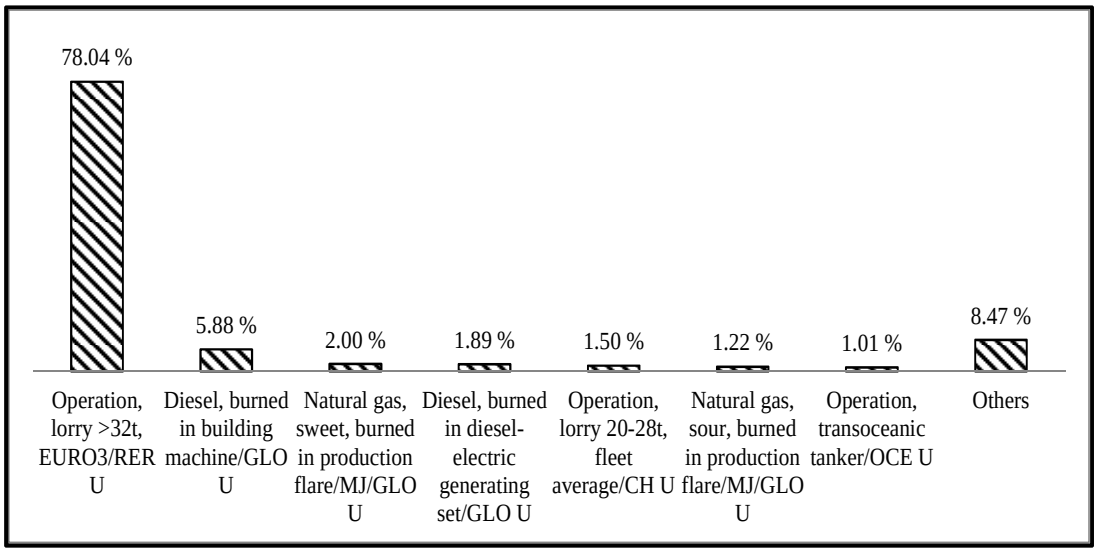


Figure F.22 Process contributions for off-highway truck in acidification category for Romania

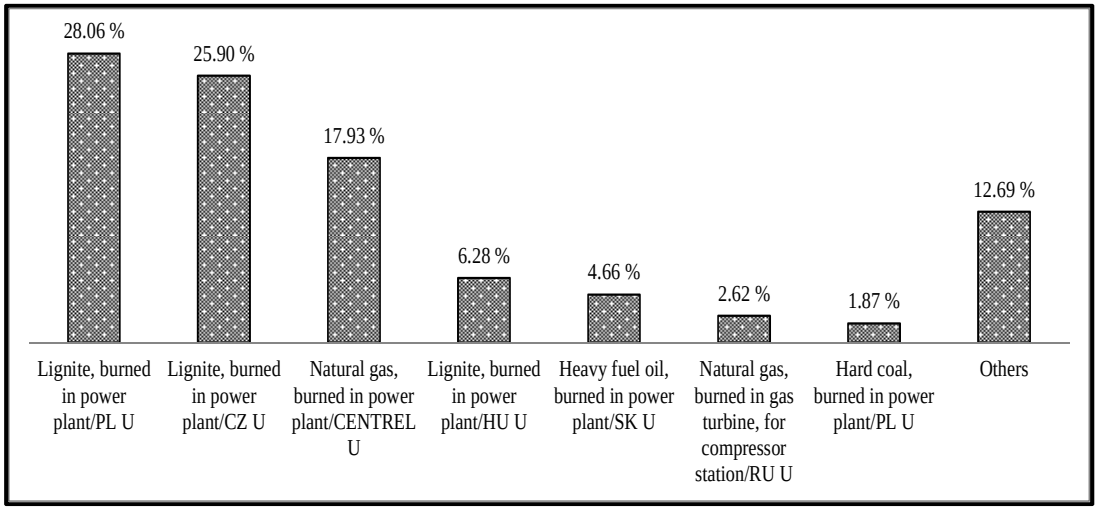


Figure F.23 Process contributions for belt conveyors in climate change category for Romania

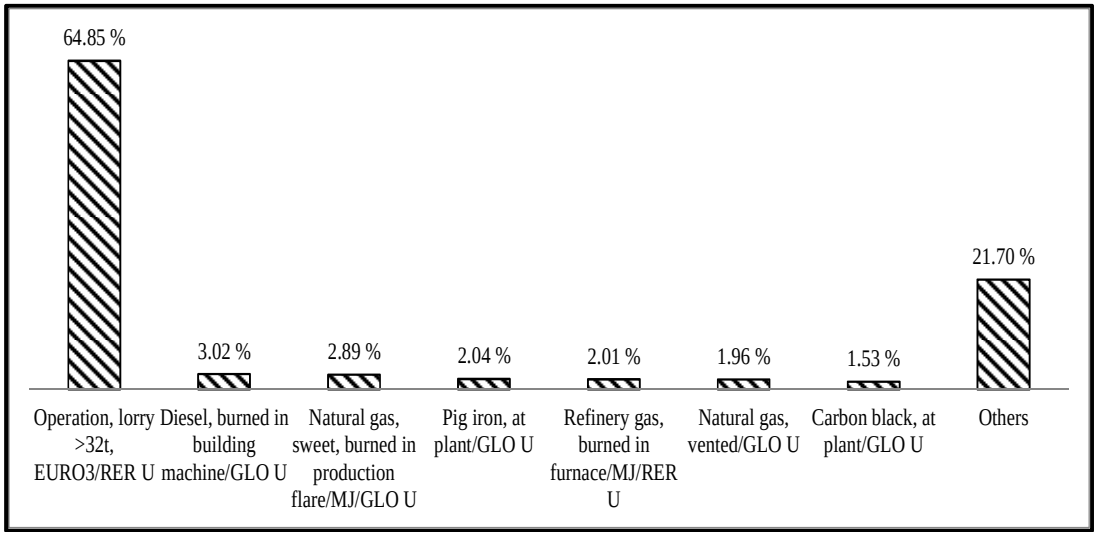


Figure F.24 Process contributions for off-highway truck in climate change category for Romania

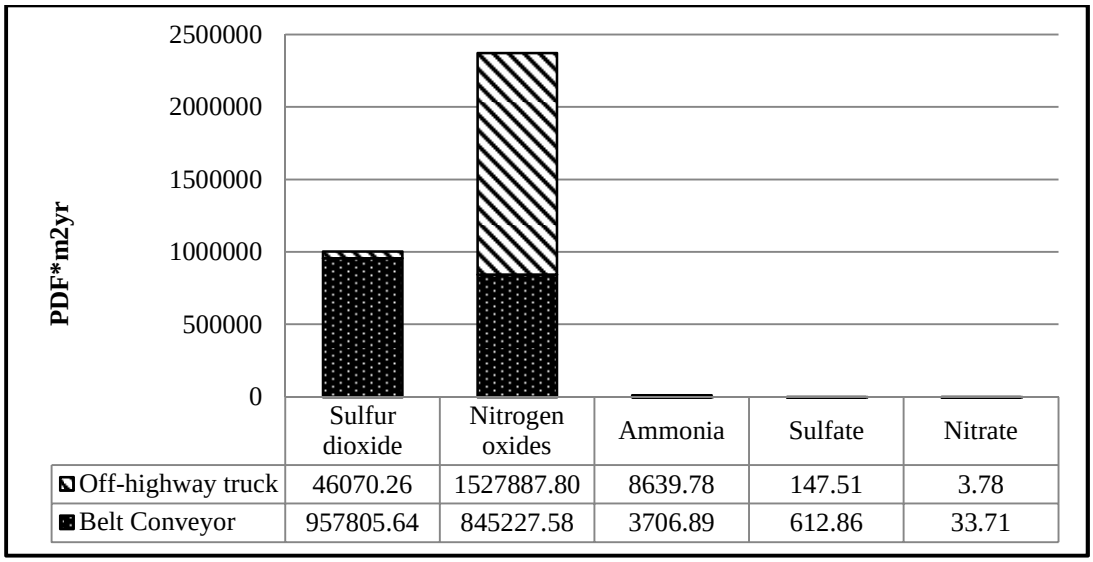


Figure F.25 LCA comparison off-highway truck vs. belt conveyor in terms of acidification for Slovenia

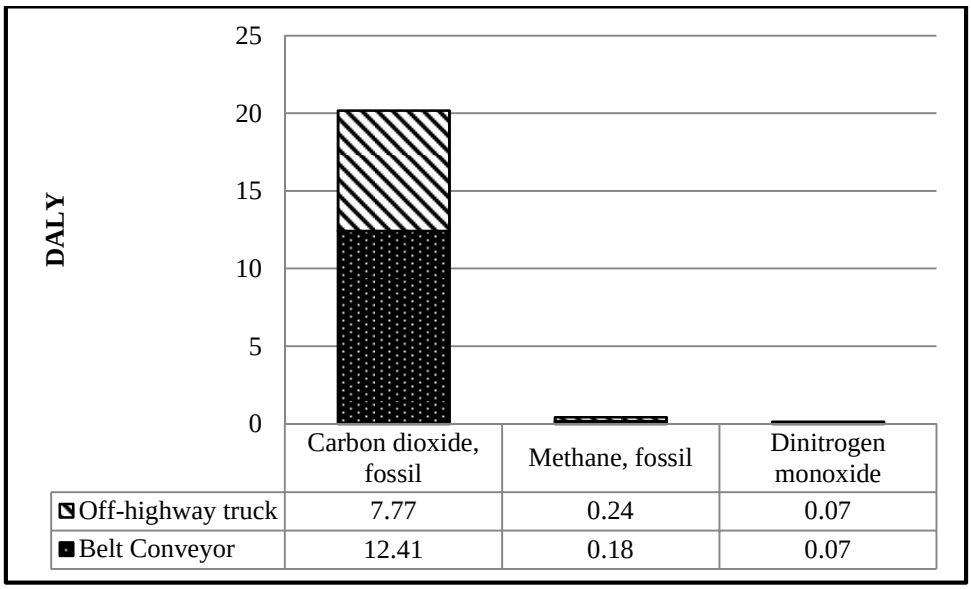


Figure F.26 LCA comparison off-highway truck vs. belt conveyor in terms of climate change for Slovenia

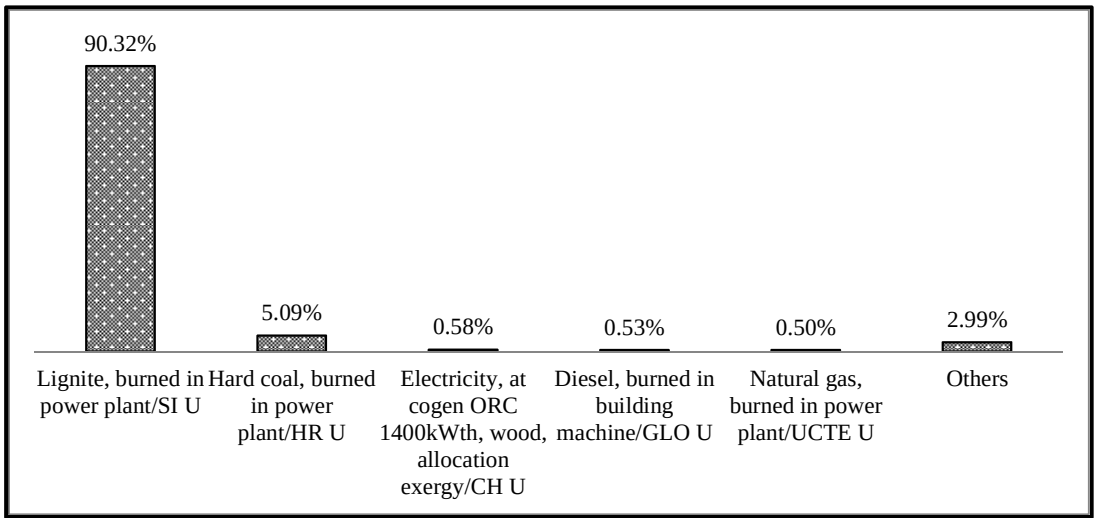


Figure F.27 Process contributions for belt conveyors in acidification category for Slovenia

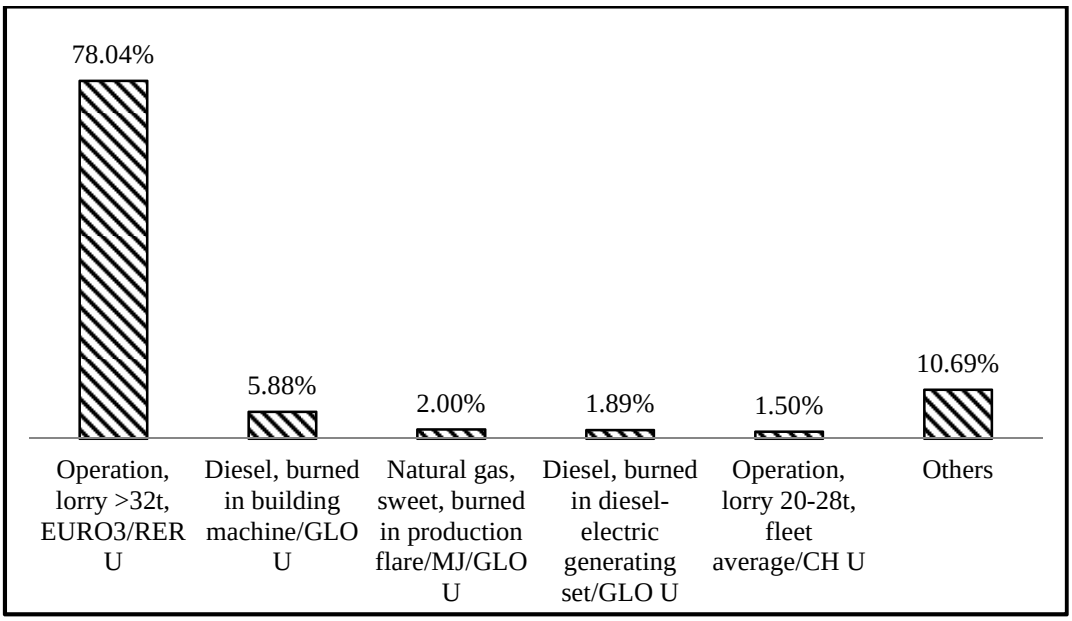


Figure F.28 Process contributions for off-highway truck in acidification category for Slovenia

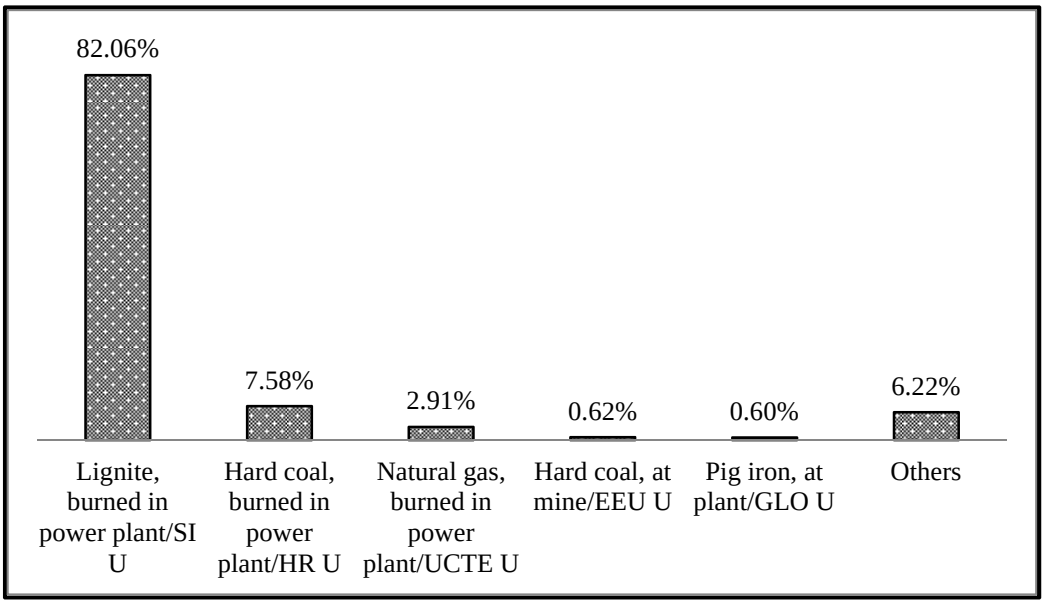


Figure F.29 Process contributions for belt conveyors in climate change category for Slovenia

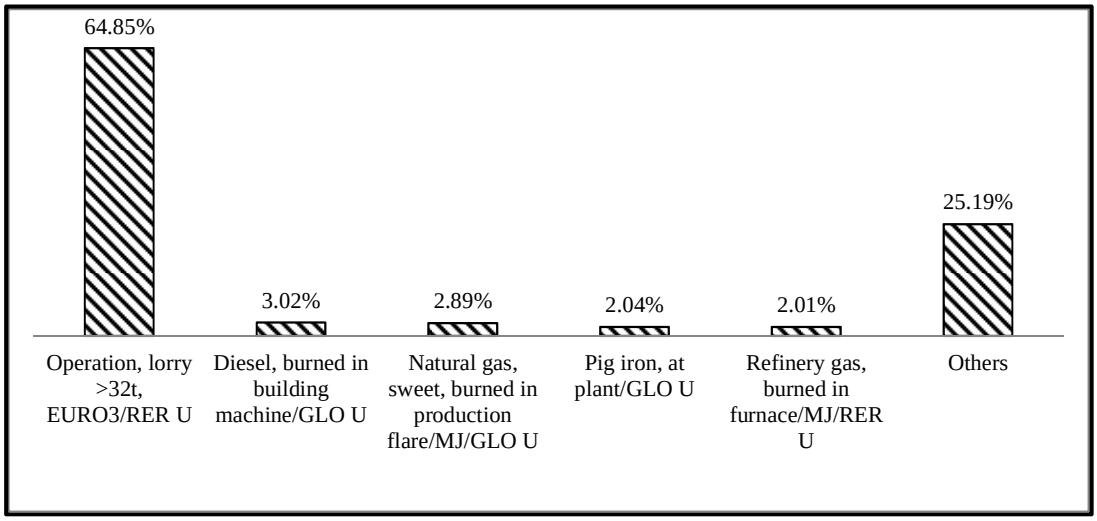


Figure F.30 Process contributions for off-highway truck in climate change category for Slovenia

APPENDIX G

MONTE CARLO SIMULATION RESULTS

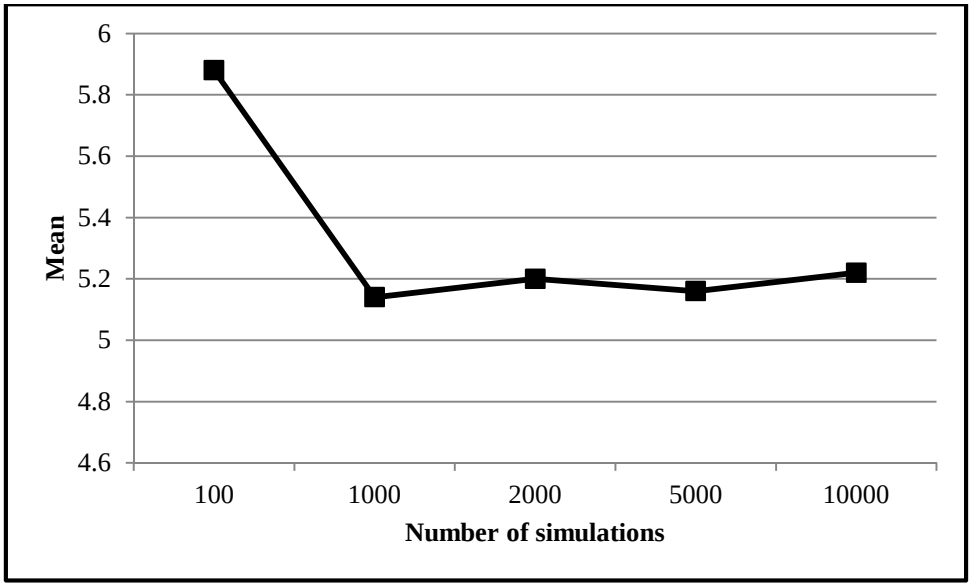


Figure G.1 Mean vs. Number of simulations for climate change

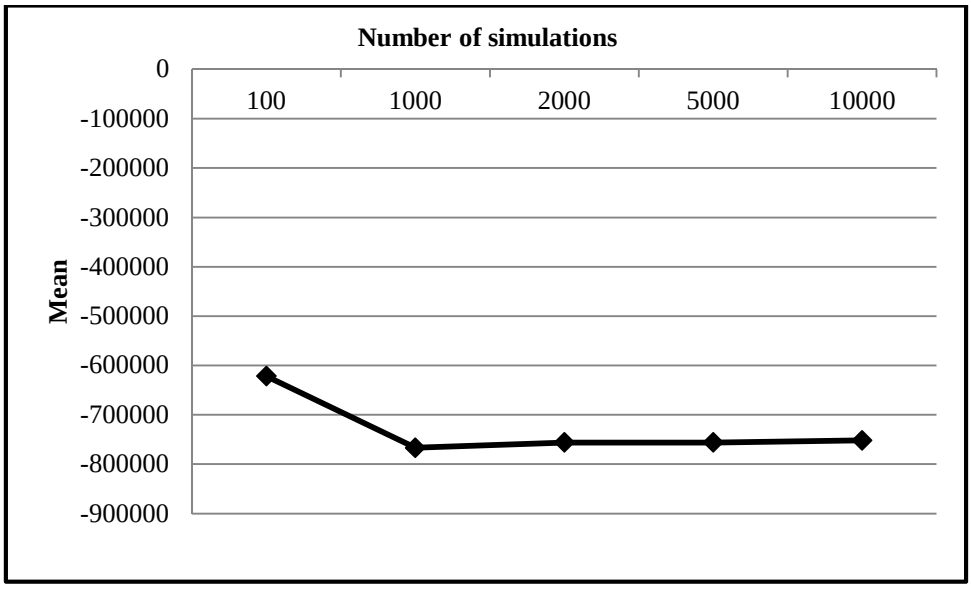


Figure G.2 Mean vs. Number of simulations for acidification

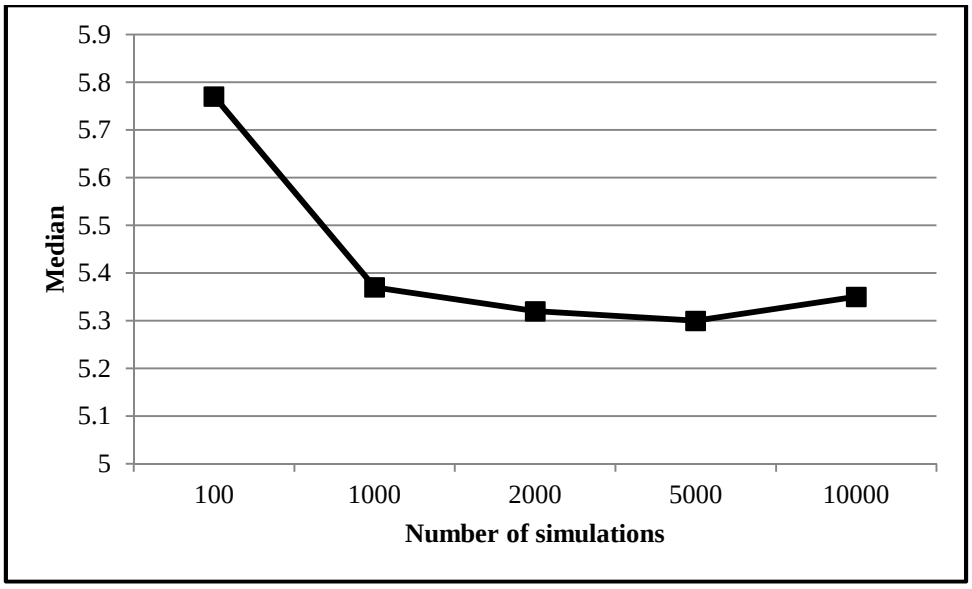


Figure G.3 Median vs. Number of simulations for climate change

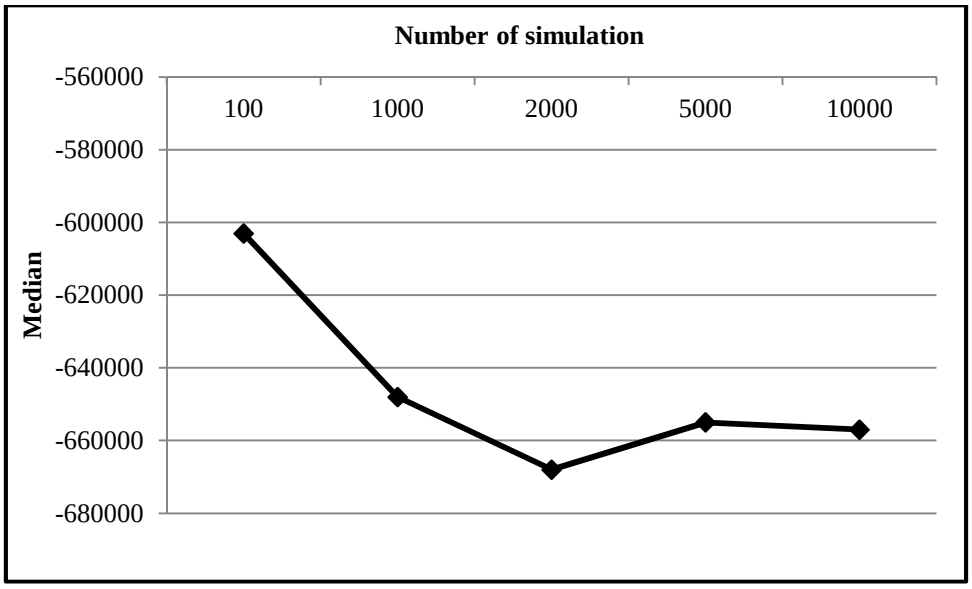


Figure G.4 Median vs. Number of simulations for acidification

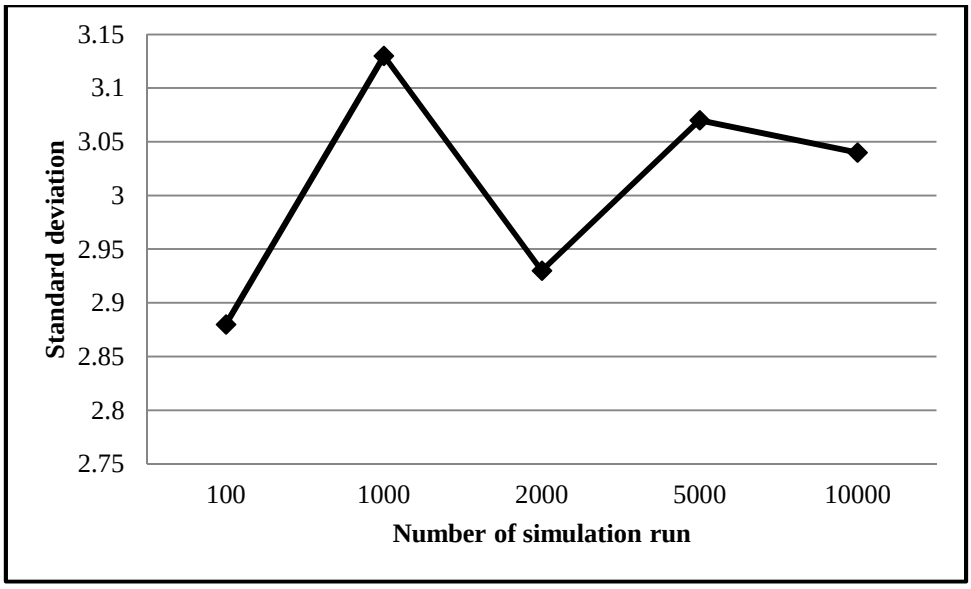


Figure G.5 Standard deviation vs. Number of simulations for climate change

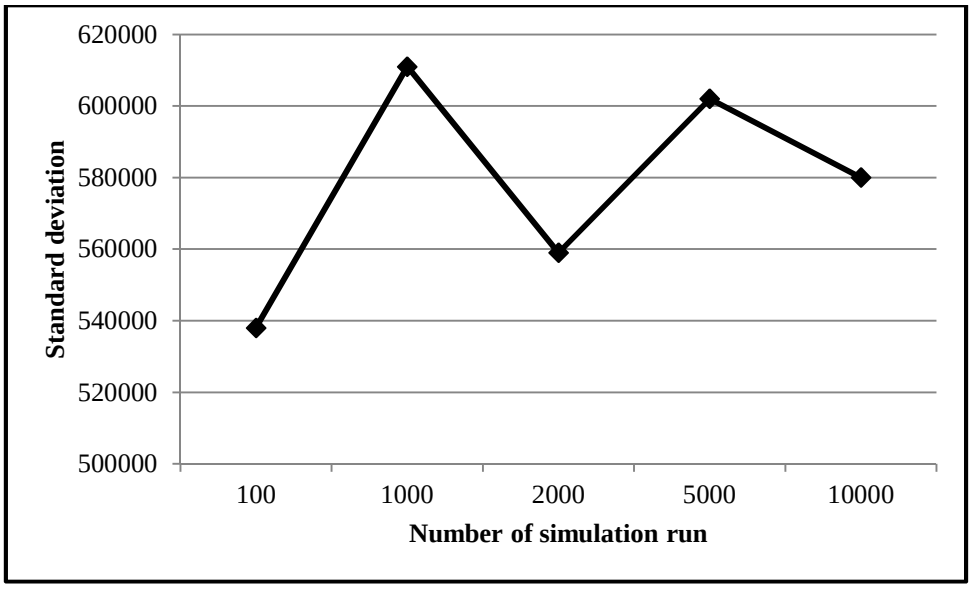


Figure G.6 Standard deviation vs. Number of simulations for acidification

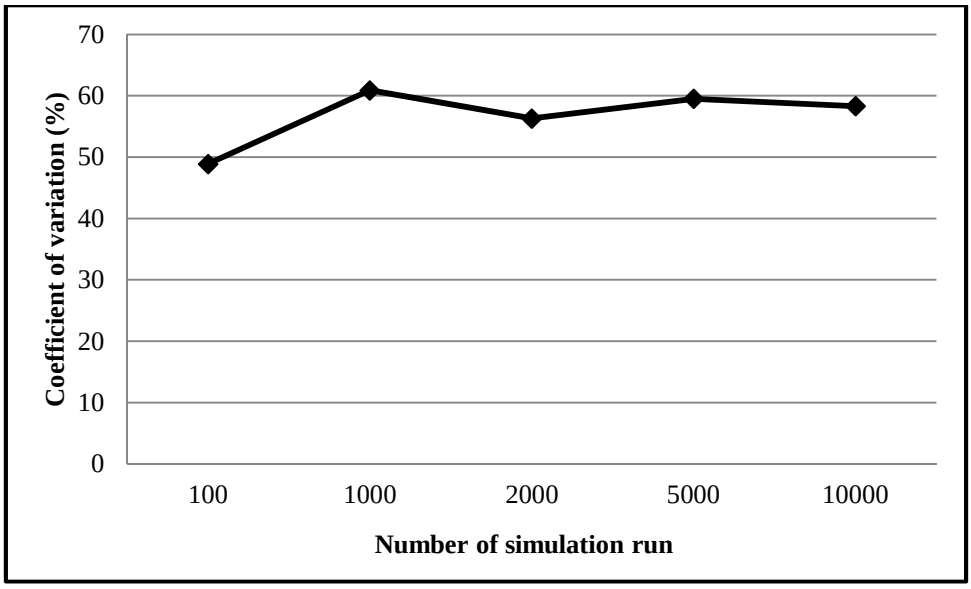


Figure G.7 Coefficient of variation vs. Number of simulations for climate change

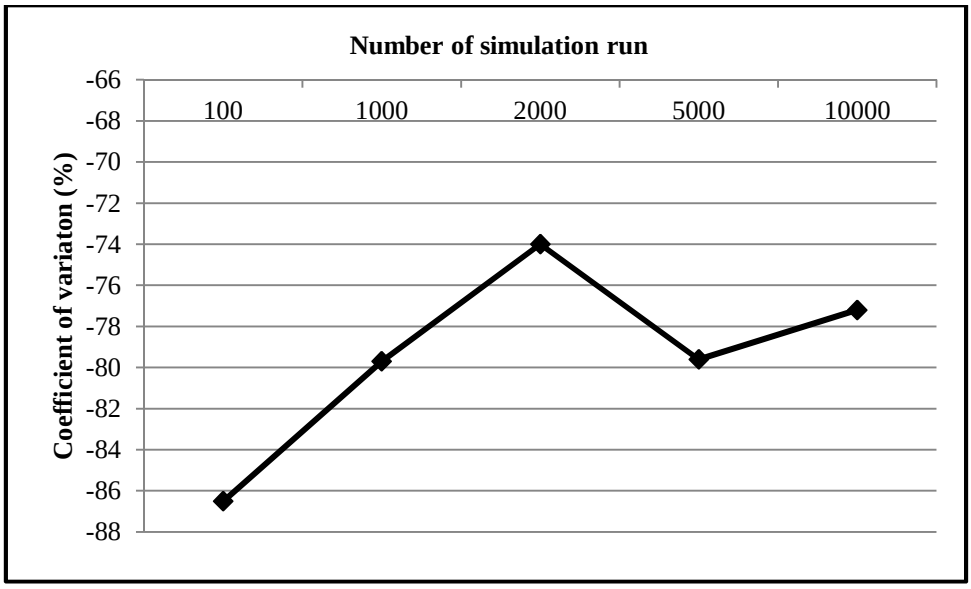


Figure G.8 Coefficient of variation vs. Number of simulations for acidification

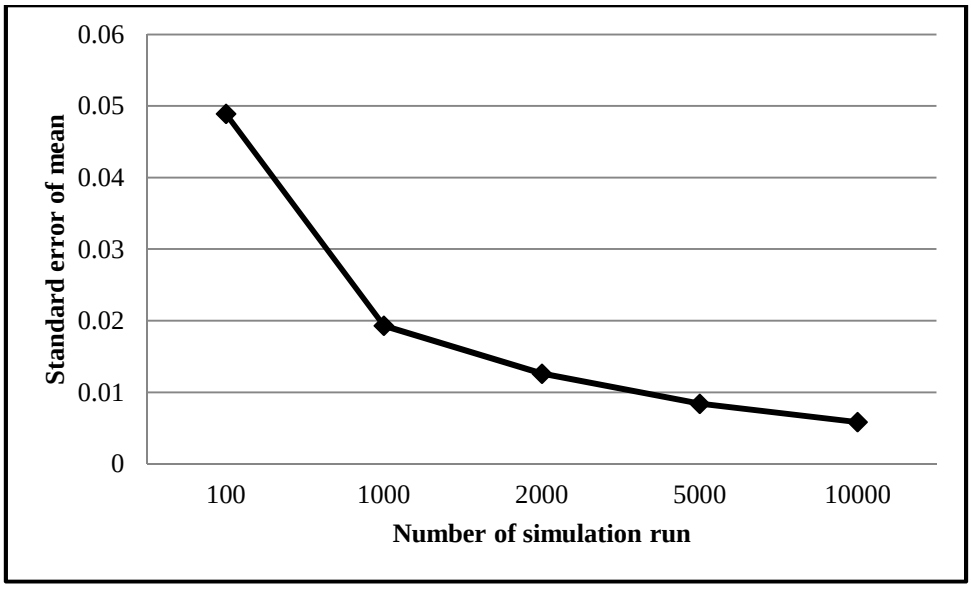


Figure G.9 Standard Error of mean vs. Number of simulations for climate change

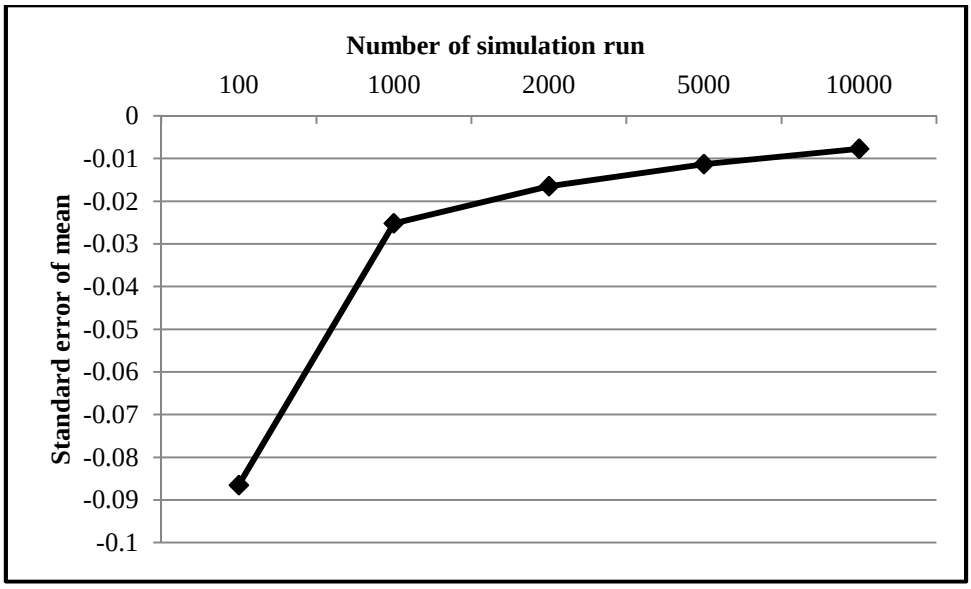


Figure G.10 Standard Error of mean vs. Number of simulations for acidification

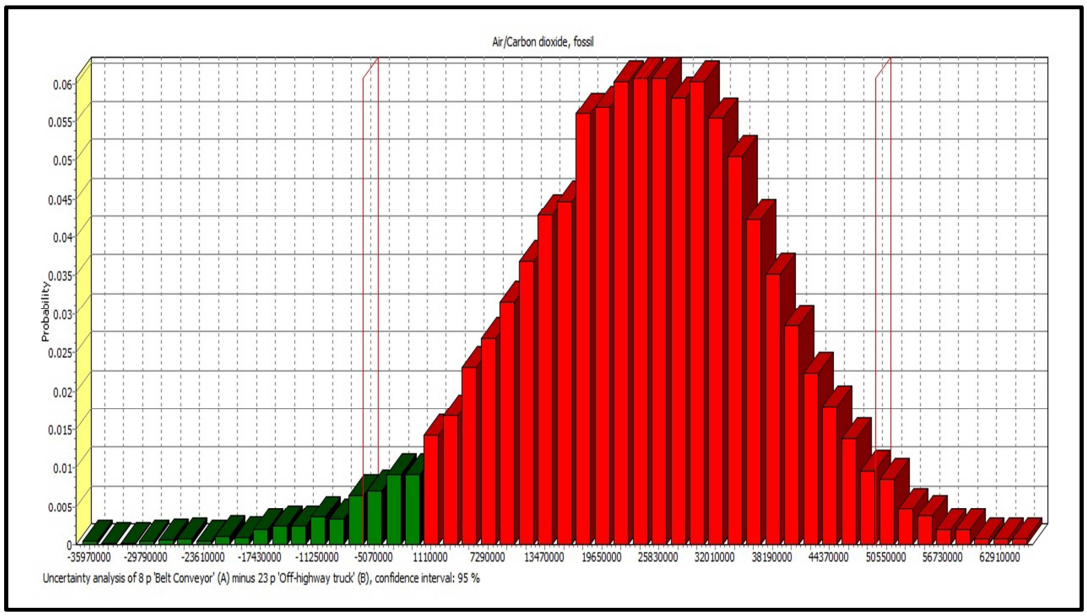


Figure G.11 Uncertainty assessment of CO_2 emission

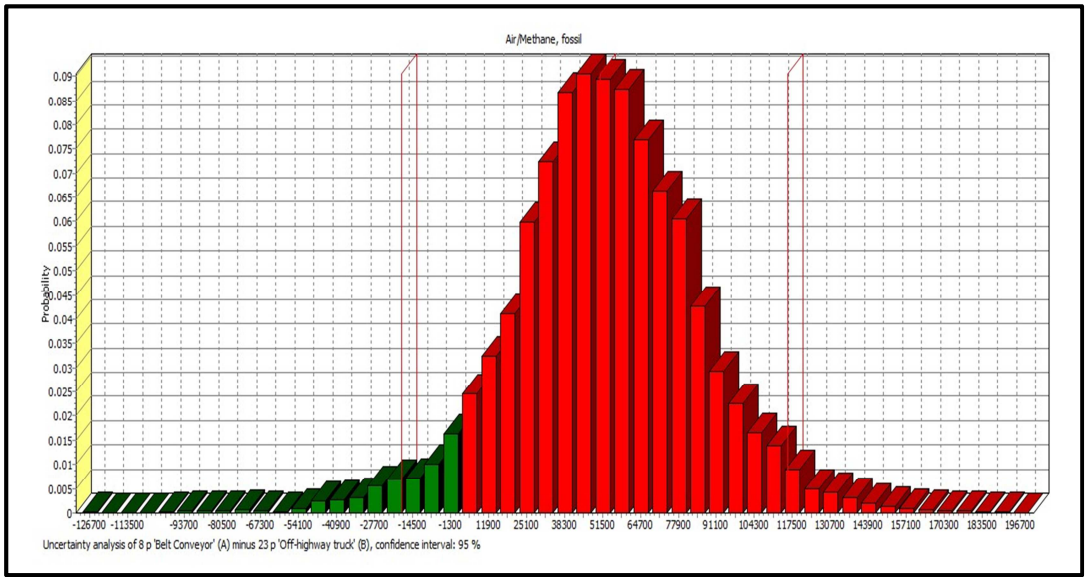


Figure G.12 Uncertainty assessment of CH_4 emission

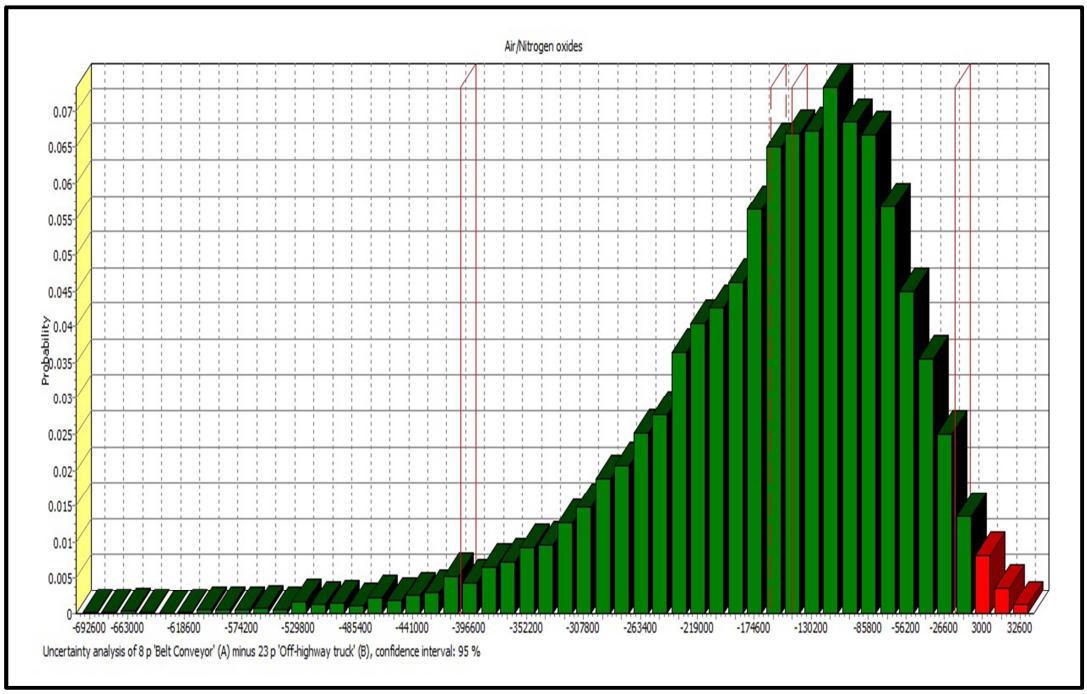


Figure G.13 Uncertainty assessment of NO emission

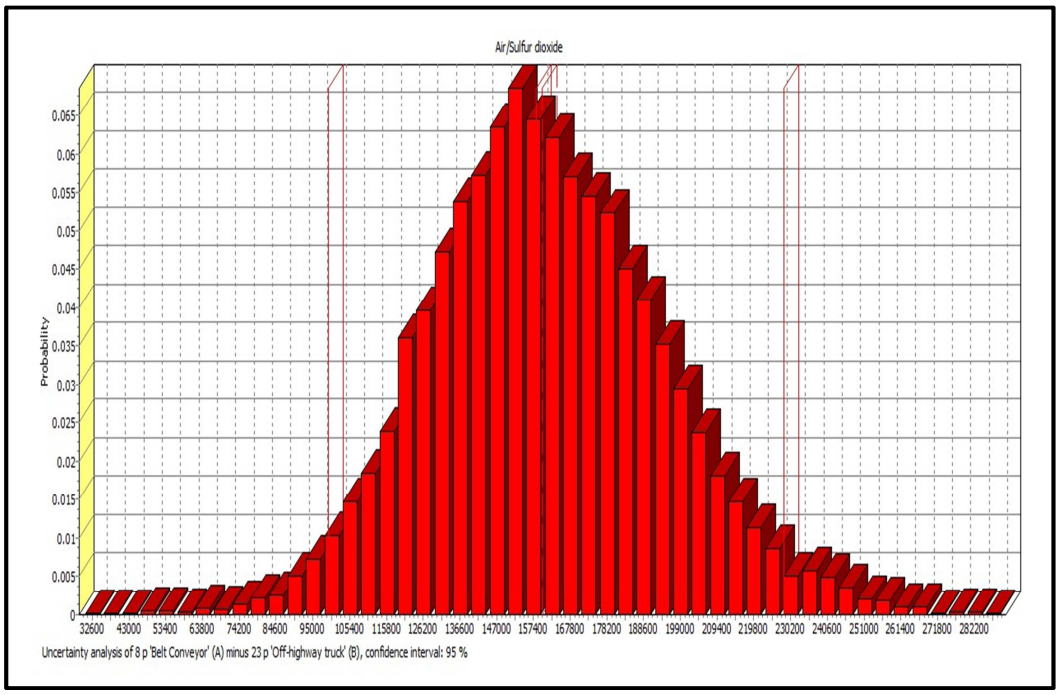


Figure G.14 Uncertainty assessment of SO_2 emission