Norsk institutt for luftforskning
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Feasibility study for asphalt rubber pavements in Norway

‘Rubber Road’ feasibility study

Evert A. Bouman, Sondre Meland, Ingvild Skumlien Furuseth,
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ABSTRACT

RubberRoad proposes to use rubber from used tires in the production of asphalt for road and bicycle ways. This recycling approach has not gained much attention in Norway despite its apparent advantages, such as noise reduction, increased durability, safer shock impact, and reduced climate and environmental impacts. The Life Cycle Analysis carried out during this project feasibility study has demonstrated a series of environmental benefits in the use of rubber in asphalt production. It has also helped identify relevant knowledge gaps related to the use phase of the rubberized asphalt and its impact to noise, air and micro-plastic pollution. Better understanding of these effects would probably result in even larger environmental benefits of rubberized asphalt with respect to standard asphalt production. However, while the tire recycling industry is generally positive to the disposal of used tires in asphalt production, additional incentives need to be put in place for the Norwegian asphalt producers to consider actively contributing to this development.

NORWEGIAN TITLE RubberRoad – Brukte dekk i asfaltproduksjon

KEYWORDS

Circular economy
Asphalt
Tires

ABSTRACT (in Norwegian)

RubberRoad foreslår å bruke gummi fra brukte bildekk i asfaltproduksjon til bil- og sykkelveier. Denne resirkuleringsmetoden er ikke særlig kjent i Norge, til tross for påviste fordeler som blant annet støyreduksjon, økt holdbarhet, støtdemping ved ulykker samt redusert klima- og miljøpåvirkning. Livssyklusanalysen, som ble utført i løpet av dette prosjektets gjennomførbarhetsstudie, har vist en rekke miljøfordeler ved bruk av gummi i asfaltproduksjon. Den har også bidratt til å identifisere kunnskapshull relatert spesielt til bruken av gummiasfalten og dens innvirkning på støy, luft og mikroplastforurensning. Bedre forståelse av disse effektene vil trolig føre til enda større miljøfordeler av gummiasfalt i forhold til standard asfaltproduksjon. Imidlertid, mens dekkgjenvinningsindustrien generelt er positiv til bruk av brukte dekk i asfaltproduksjon, må det legges til rette for ytterligere incitamenter for at norske asfaltprodusenter skal vurdere å bidra aktivt til denne utviklingen.

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Preface

This report was prepared as part of a research feasibility study for asphalt rubber pavements in Norway in the period September-December 2018. In line with the ideas behind the circular economy, the study, called 'RubberRoad', investigated the potential life-cycle environmental (LCA) impacts of re-using rubber granulate produced from End-of-Life Tires (ELTs) in asphalt production and road construction. A PESTLE (political, economic, socio-cultural, technological, legal and environmental) analysis was also carried out in a series of workshops to identify barriers for implementation of this technology in the Norwegian context. The project was carried out by the Norwegian Institute for Air Research (NILU) and the Norwegian Institute for Water Research (NIVA). The study was funded by Norsk Dekkretur, RagnSells Dekkgjenvinning AS, and the Research Council of Norway (RCN).

Norsk Dekkretur and RagnSells Dekkgjenvinning AS helped organising and participating at the two stakeholder meetings organised during the project. NILU was responsible for carrying out the LCA analysis and NIVA carried out the PESTLE analysis. Norsk Dekkretur AS has served as project contact point with rubber asphalt producers and recycling companies. RagnSells Dekkgjenvinning AS provided a useful reference and link to the sustainability analysis for rubberized asphalt currently carried out in Sweden.

The authors are very thankful to the co-founders of this study and in particular to Jon-Erik Ludvigsen from Norsk Dekkretur and Sara Stiernström and Kristin Johansson from RagnSells Dekkgjenvinning AS for valuable discussions and their encouraging support.

Contents

Summary

Used tires represent a significant waste problem both globally and in Norway, with ca. 60,000 tons of tires been discarded in our country every year. It is not allowed to dump used tires in a landfill. Instead, tires are burned for energy or recycled for example for use as filler in artificial soccer fields. However, the waste treatment methods for used tires currently used in Norway leads to serious environmental and climate effects, including harmful emissions of micro-plastics and chemicals to water, air, and soil. Therefore, alternative more sustainable ways to dispose of our used tires need to be considered.

The RubberRoad project proposes to use rubber from used tires in the production of asphalt for road and bicycle ways. This recycling approach has not gained much attention in Norway despite is apparent advantages, such as noise reduction, increased durability, safer shock impact, and reduced climate and environmental impacts. Therefore, the current report constitutes an initial feasibility study with a main aim to motivate the Norwegian asphalt industry to cooperate with tire recycling enterprises to use rubber in asphalt production as an international competitive asset. It is also intended to contribute to make the Norwegian tire and asphalt sector greener and more sustainable in an international perspective, thus contributing to the move from a linear to a circular economy.

The potential life-cycle environmental (LCA) impacts of re-using rubber granulate produced from End-of-Life Tires (ELTs) in asphalt production and road construction is presented here. Our screening LCA analysis compares the environmental impacts from asphalt containing 20% rubber in the bituminous binder - asphalt rubber - with conventional asphalt. The study incorporates both the production of the asphalt mix, subsequent laying of the asphalts, resurfacing the roads after the service life of the asphalt, as well as the difference in emissions from transport during road use. Our LCA analysis has shown how increased use of ELTs in asphalt production is expected to reduce the need for polymer-based bitumen using ELTs as a secondary raw material and how there is an environmental benefit when using asphalt rubber solutions in comparison with standard asphalt. Still, there is a need for further understanding of the life span of both tires and the asphalt, the emission of particles, including micro particles and chemicals but also the characteristics including noise reduction, and resistance and elasticity.

A PESTLE (political, economic, socio-cultural, technological, legal and environmental) analysis has also been carried out in a series of workshops to identify barriers for implementation of this technology in the Norwegian context. The analysis has identified several knowledge gaps and significant barriers for uptake by asphalt producers. The main concerns by asphalt producers were related to smell, micro-plastic emissions and recyclability of rubber asphalt and it is clear that additional incentives need to be put in place for the Norwegian asphalt producers to consider actively contributing in further research on rubber asphalt or possibly testing it on Norwegian roads.

Feasibility study for asphalt rubber pavements in Norway

'Rubber Road' feasibility study

1 Introduction

Transport and mobility are an integral part of everyday life and are fundamental to modern society. European society and its economy rely heavily on motorized road transport for the movement of both goods and persons (European Commission 2011, 2012). The exhaust emissions associated with road transport are often focused in the context of the necessary reduction of greenhouse gas emissions (GHGs) and urban air pollution, which lead to respectively climate change and negative effects on human health. While technology advances aim to reduce the extent of GHG and pollution from exhaust emissions, less effort is addressed to reduce road particulate matter released through tire wear, brake wear, and road wear. Increasing urbanisation and traffic, together with global transportation of goods, contribute to large emissions of tire wear particles (TWP) and a growing number of discarded tires. The annual number of discarded tires is substantial so that the so-called "End-of-Life Tires (ELTs)" constitute a significant and growing waste problem.

Used tires (ELTs) constitute in increasing waste problem both in Norway and globally. While tires are not produced in Norway, they are sold, used and recycled in large numbers, with about 60,000 tonnes of tires discarded annually (Dekkretur 2018). It is not allowed to landfill ELTs, causing a challenge on how to deal with an increasing number accumulating every year. In 2017, most ELTs (72%) was combusted for energy recovery. A smaller fraction (24%) entered the material recovery stream (Norsk Dekkretur, 2018).This situation demands new and innovative ways for recycling and repurposing ELTs.

Typically, ELTs are burned for energy recovery or recycled for material recovery. While the combustion of ELTs as a disposal route has its advantages, it does result in emissions of greenhouse gases as well as the formation and release of dangerous chemicals. Material recycling offers a potentially more environmentally friendly alternative. Whole tires are used in the construction of noise barriers, tire chips are used as drainage or insulation, and granulates are used as infill in artificial soccer fields or mixed into asphalt (Torretta et al., 2015). However, the use of loose ELT granulates in an open environment leads to new challenges such as the non-intentional emissions of micro-plastics into water, air and soil surrounding artificial turfs as well as the possibility of leaching harmful chemicals. While there is still uncertainty related to the magnitude and effects of these releases, significant societal attention has led to negative opinions on the use of rubber granulate in this context. Thus, recycling or repurposing applications of ELTs where the granulate is sequestered, minimizing the risk of release of micro-plastics and harmful chemicals, are of interest. In addition, it is important that these waste management options are of sufficient scale to accommodate the large amounts of ELTs available annually.

One such application is the use of rubber granulate from ELTs in the production of asphalt to produce what is denominated Asphalt Rubber or Rubberized Asphalt depending on the amount of tire rubber mixed into the asphalt. This recycling approach has been tried in different countries (US, Canada, Portugal, China) and is currently been evaluated in Sweden. In contrast, the use of tires in asphalt production has not gained much attention in Norway despite the apparent advantages such as noise reduction, higher rutting resistance, increased durability, breaking black ice, thinner layers, reduction of cracking, distinct road separation/striping, shock absorption, reduction of carbon dioxide (CO_2) emissions and energy savings (Andren & Hedin 2018).

A sustainability analysis of the production of rubberized asphalt throughout its life cycle is currently missing in Norway. There are also few studies that quantify and systematically evaluate the potential environmental impacts related to rubber containing asphalt in comparison with regular asphalt. Such a comparison may be made by applying Life Cycle Assessment (LCA), a method to quantify potential environmental impacts associated with a product or product system throughout its life cycle. Some LCA studies have been published on either ELTs, road pavement, or asphalt rubber. For example, see (Fiksel et al., 2011, Chiu et al., 2008, White et al., 2010, Bartolozzi et al., 2012, Farina et al., 2017, Johansson, 2018). However, most studies differ in scope and system boundaries which complicates the comparative case. For example, some studies only consider the production of the asphalt (Fiksel et al., 2011), while effects associated with asphalt laying, road maintenance, and road use may have larger effects (Santero et al., 2011b, Santero et al., 2011a). Others focus solely on greenhouse gas emissions (White et al., 2010) and ignore other potential environmental impacts, such as the aforementioned air quality issues. In addition, following the recommendations adopted by the European Asphalt Pavement Association (EAPA 2017). on the use of secondary materials in asphalt production, it is necessary to carry out risk assessments that demonstrate how the incorporation of secondary materials fulfils several criteria related to health and safety, environment, recyclability of asphalt, technical product performance, value for money and competitiveness. These criteria should be addressed when assessing the potential use of reclaimed tires in asphalt production.

This report provides an initial comparison between the life cycle environmental impacts of asphalt rubber and regular asphalt in Norway, including the laying of the asphalt layers, and the use of the road. Through this LCA comparison, we aim to quantify the magnitude of individual contribution of the asphalt rubber life cycle to overall environmental impacts, as well as identify current gaps in knowledge that would require further investigation. The report is divided in three parts. The first part, including Chapters 2, 3 and 4, presents our LCA methodology, data and the main results. The second part of the report, including Chapters 5 and 6, presents our PESTLE (political, economic, socio-cultural, technological, legal and environmental) analysis summarizing the main obstacles and limitations of sustainable rubberized asphalt production in the current conditions in Norway. The third part includes only Chapter 7, where the main conclusions from our feasibility study are discussed and summarized.

PART I
Life Cycle Assessment

2 LCA methodology

The goal of the LCA presented in this report is to provide an initial comparison between the life cycle environmental impacts of asphalt rubber and regular asphalt in Norway, including the laying of the asphalt layers, and the use of the road. Where possible, data specific to Norway are used. For example, the Norwegian electricity mix is used for tire granulation. However, due to the relatively poor availability of Norwegian processes in both the ecoinvent database as well as the scientific literature, proxies may be used. Where available these proxies will be based on European data, but for some processes global datasets are the only ones available. This results from this LCA are primarily intended for stakeholders interested in the potential environmental impacts of asphalt rubber as a means of utilizing ELT waste. While a more detailed and thorough environmental impact assessment will have to be carried out for specific projects, this LCA will shed light on the magnitude of potential environmental impacts as well as potential focus areas for further research.

Life Cycle Assessment (LCA) is used as an analytic tool to quantify and assess the full range of potential environmental impacts of the technological system based on a holistic view, including direct- and supply chain impacts. The motivation is to assist decisions, policies and strategies towards environmentally sound solutions. A typical LCA consists of four phases: 1) goal and scope definition, 2) life cycle inventory, 3) impact assessment and 4) interpretation. The LCA procedure is standardized in ISO 14040, though the standard allows for a multitude of approaches (ISO 14040 International Standard, 2006).

The goal and scope of the LCA relates to the system under investigation, and defines the LCA method employed, and a reference flow for the entire study, the functional unit, is established. A life cycle inventory (LCI) includes information on all the environmental inputs and outputs associated with a product system as well as all product and service flows across the product system. To create an LCI, an inventory of flows to and from the environment must be created. Flows may include inputs of water, energy, raw materials and waste (both natural and man-made), and releases to air, land and water. Constructing an LCI is a data intensive exercise. LCAs therefore rely on the use of commercial LCI databases. An LCI database is a collection of datasets (inventories) providing information for a large number of standard processes. The system under investigation is referred to as a ‘foreground’ system, which is connected to the database - the ‘background’ system.

An LCI results in the life cycle emissions of singular environmental stressors, such as carbon dioxide, methane, or benzene. However, the vast number of potential environmental stressors complicates communication of individual results. Stressors are therefore grouped in meaningful impact categories, by quantifying their contribution to impact indicators. This is the impact assessment step of LCA. There are several impact assessment methods available (e.g. EcoIndicator99, ReCiPe, CML2001), and impacts are expressed either at midpoint (e.g. toxicity), or at endpoint (e.g. damage to human health) level.

The present report uses a comparative attributional LCA, i.e. potential environmental impacts are attributed to the functional unit, which is established to be 1 km of 2-lane road, with a total width of 7 m, over a period of 40 years. The background LCI database used in ecoinvent v3.3 and CML2011 and ReCiPe were used as impact assessment methods, both provided by ecoinvent (Frischknecht et al., 2005). Custom LCA software was used for the LCA calculations.

3 Life Cycle Inventory

In the following sections we describe the several stages of the life cycle modeled for this project. Two cases are compared: i) a road with a rubber asphalt top-layer and ii) a road constructed with a 'classical' asphalt top layer. As the comparative assessment is made between the various types of asphalt, other elements necessary for road construction are considered outside the scope of this assessment. Thus, the production and construction of the roadbed and road base are not included in this assessment as they are assumed independent of the wearing and binder course and as such do not contribute to the comparative analysis. This also implies that the presented results are not a quantification of the total environmental impacts associated with road construction. Rather, the results refer to those impacts associated with the asphalt pavement. Table 1 lists the key parameters for the two cases. Note that they differ on two aspects. The lifetime of asphalt rubber pavement is considered longer than the lifetime of the reference asphalt and a thicker three-layer reference asphalt is assumed necessary for similar functionality. Reports on the service life of the top layer vary considerably. Chiu et al. (2008) report a lifetime of 9 year for the asphalt rubber and a 6 year lifetime for conventional asphalt, with both top layer 5 cm thick. Bartolozzi et al. (2012) report an 8-year lifetime for asphalt rubber and a 5-year lifetime for conventional asphalt for respectively a 3 and 4 cm layer. White et al. (2010) uses a ratio of 2.5" to 4" for asphalt rubber compared to conventional asphalt with layers of equal thickness. Finally, Johansson (2018) model a lifetime of 8.3 years for asphalt rubber and 4.6 years for conventional asphalt, with in respectively a two or three layer configuration. In this study, as a base case for asphalt rubber a lifetime of 9 years was chosen for a 4 cm asphalt rubber layer on top of a 5 cm asphalt rubber layer. For the reference asphalt, a lifetime of 6 year was chosen for a 4 cm top layer on top of two layers of respectively 4 and 5 cm. As there is large uncertainty associated with the lifetime and thickness of asphalt layers, these will be further investigated in the uncertainty analysis in section 4.2.

Table 1: Key parameters for the two cases.

Parameter	**Asphalt rubber**		**Reference asphalt**	
	Value	*Unit*	*Value*	*Unit*
Road length	1000	m	1000	m
Road width	7	m	7	m
Asphalt layers	4 (top) + 5	cm	4 (top) + 4 + 5	cm
Road lifetime	40	yr	40	yr
Top layer lifetime	9	yr	6	yr
Resurfacing	3.44	times	5.66	times

The following processes are considered in the LCA model. Production of the rubber granulate, bitumen, and aggregates, asphalt production and laying of the top wearing course and other courses, road maintenance through milling the top layer and resurfacing with new asphalt, road use and finally the transport of raw materials and intermediate goods. An overview of the system is given in Figure 1. In the following subsections, the in- and outputs of each of the modelled processes will be presented in detail.

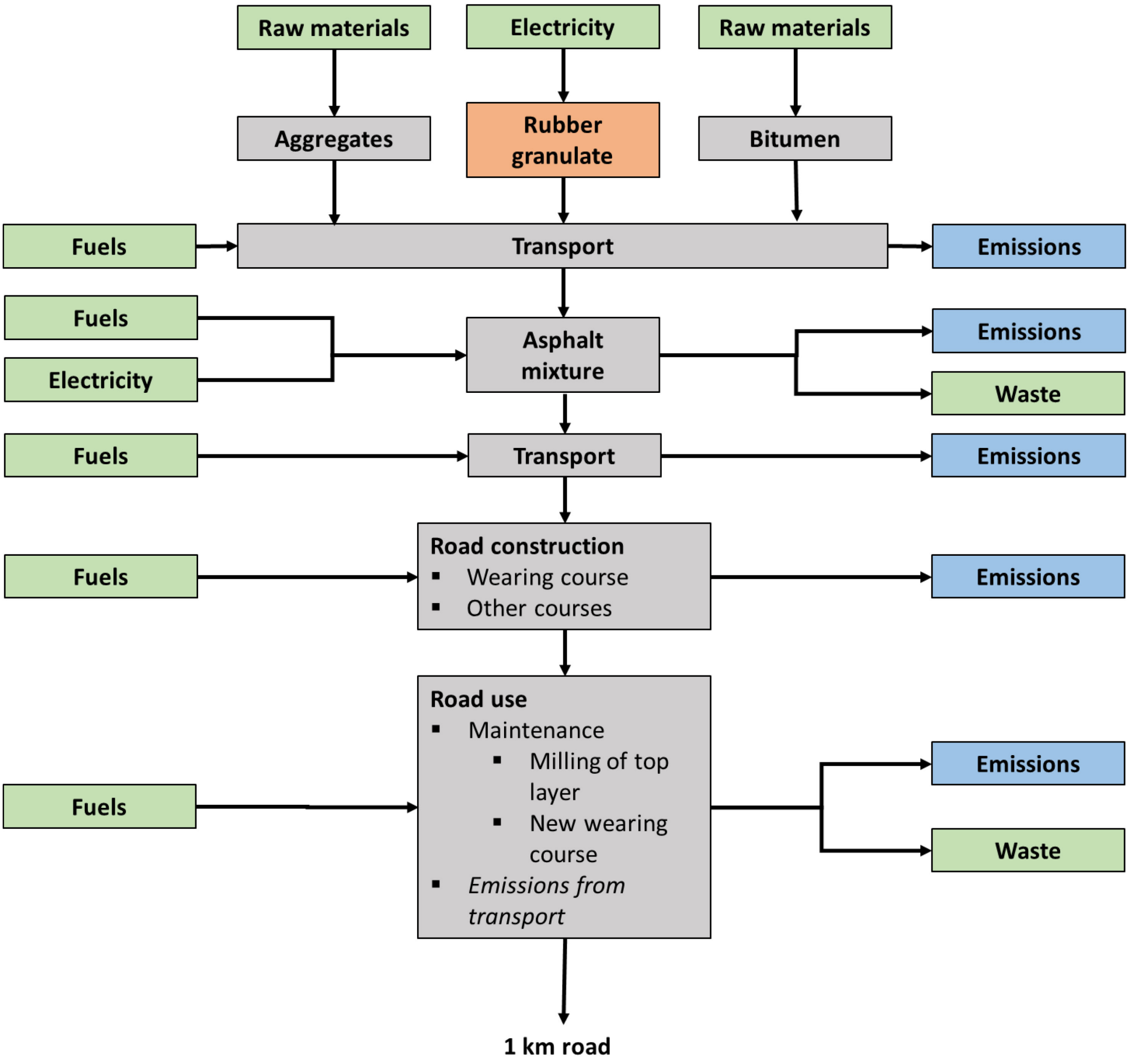


Figure 1: System boundaries of the LCA study. The main system modelled is shown in grey and the production of rubber granulate from ELTs is highlighted in orange. This process is not included in the model for the reference asphalt. The flows for raw materials, electricity and fuels indicate that here the system is using data from the LCI database ecoinvent v3.3. Emissions to the environment are indicated in blue.

3.1 Production of rubber granulates

The production of rubber granulates is modelled based on the values presented in (Johansson, 2018). Table 2 shows the material, transport and energy requirements to produce 1 kg of granulate from rubber tires. Note that 1.73 kg of ELTs is required for producing 1 kg granulate. In addition, a tire generates 0.34 kg steel and 0.34 kg of textiles. However, we take a conservative approach and all impacts are attributed to the rubber granulate. The Norwegian electricity mix is used to model electricity and an amount of 0.37 kWh was chosen as the required energy for the granulation process, though higher amounts, up to 0.53 kWh/kg have been reported in the literature (Bartolozzi et al., 2012, White et al., 2010).

Table 2: Rubber granulate production. NO – Norway; EUR – Europe; EwS - Europe without Switzerland.

Parameter	**Asphalt rubber**		**Reference asphalt**		**Reference**
Reference product	*Value*	*Unit*	*Value*	*Unit*	
Rubber granulate	1	kg	n. a		Johansson, 2018
Inputs					
Electricity, NO	0.37	kWh			
Transport, lorry, EURO6, EUR	0.2595	t*km			
ELTs	1.73	kg			
Waste					
Inert waste, EwS	0.05	kg			

3.2 Asphalt production

Asphalt production is modelled as a mixture of rubber granulates, bitumen and aggregates. Table 3 gives an overview of the process. No direct emissions are specified here as the energy combustion processes are taken from the ecoinvent database and therefore include the major emissions during the asphalt production process. Data for this process was taken from (Johansson, 2018) and (White et al., 2010) and represent a mix of 20% rubber in the rubber-bitumen binder mix.

Table 3: Asphalt production. RoW – Rest-of-the-World;

Parameter	**Asphalt rubber**		**Reference asphalt**		**Reference**
Reference product	*Value*	*Unit*	*Value*	*Unit*	
Asphalt rubber	1	kg			
Asphalt			1	kg	
Inputs					
Rubber granulate	0.016	kg	n.a.		White, 2010
Bitumen, EwS	0.064	kg	0.05	kg	White, 2010
Aggregates, RoW	0.92	kg	0.95	kg	White, 2010
Heat, LFO, EwS	0.304	MJ	0.285	MJ	Johansson, 2018
Electricity, NO	0.015	kWh	0.01	kWh	Johansson, 2018
Transport, lorry, EURO6, EUR	0.0956	t*km	0.085	t*km	Johansson, 2018

3.3 Asphalt laying

Due to the addition of the granulate, asphalt rubber and reference asphalt have different densities, which are 2456 and 2570 kg/m3. However, the asphalt laying process is normalized per m2, with a layer thickness of 4 cm, which results in more asphalt being required per m2 for the reference asphalt than for the asphalt rubber. Data for road construction equipment was found in Bartolozzi et al. (2012), who supply data for the paver, bobcat, road sweeper and roller. Fuel consumption per m^2 asphalt was given as respectively 18.1 L/h, 4 L/h, 26.67 L/h, and 12.85 L/h. Hourly surface coverage by the equipment was respectively 1000 m^2, 16000 m^2, 8000 m^2, and 4000 m^2. Using a diesel density of 0.832 kg/L these consumption data were related to the ecoinvent background process for diesel consumption in building machines.

The asphalt laying process also includes emissions of non-methane volatile organic compounds (NMVOCs) and polycyclic aromatic hydrocarbons as these chemicals can be considered harmful for ecotoxic. However, data was not readily available for this process and were established by the following proxy. Based on an air quality measurements Jullien et al. (2006) provide total NMVOC and PAH flows of respectively 1976 mg/m2h and 0.11 ug/m2h. Assuming that the asphalt is sufficiently cooled within 1 hour we can ignore the time dimension of the flow rates. Zanetti et al. present measurements on emission of individual compounds from asphalt rubber and conventional asphalt (Zanetti et al., 2014, Zanetti et al., 2016). However, emissions are presented as concentrations at the paver driver seat and screed, rather than flows. We calculated the fraction of the different compounds and scaled this with the total flow rates. The average concentrations from conventional asphalt were approximately 80% of average concentrations of asphalt rubber and this was reflected by adjusting the flow rate scale.

Table 4: Asphalt laying. GLO – global.

Parameter	**Asphalt rubber**		**Reference asphalt**		**Reference**
Reference product	*Value*	*Unit*	*Value*	*Unit*	
Asphalt rubber, laid	1	m2			
Asphalt, laid			1	m2	
Inputs					
Asphalt rubber	98.3	kg			
Asphalt			103	kg	
Transport, lorry, EURO6, EUR	9.83	kg	10.3	kg	Johansson, 2018
Paver (diesel), GLO	0.644	MJ	0.644	MJ	Bartolozzi, 2012
Bobcat (diesel), GLO	0.00889	MJ	0.00889	MJ	
Road sweeper (diesel), GLO	0.119	MJ	0.119	MJ	
Roller (diesel), GLO	0.114	MJ	0.114	MJ	
Emissions					
Benzene	1.12E-04	kg	5.11E-05	kg	Zanetti, 2016, Zanetti, 2014, and Jullien, 2006
Toluene	1.98E-04	kg	1.47E-04	kg	
Benzene, ethyl-	1.27E-04	kg	1.41E-04	kg	
Xylene	2.77E-04	kg	1.59E-04	kg	
Styrene	7.03E-06	kg	2.49E-06	kg	
NMVOC, unspecified	1.25E-03	kg	1.44E-03	kg	
Naphthalene	6.17E-12	kg	2.76E-12	kg	
Acenaphthylene	1.49E-12	kg	1.10E-12	kg	
Acenaphthene	1.50E-12	kg	1.63E-12	kg	
Fluorene	7.70E-12	kg	2.17E-12	kg	
Benzo(b)fluoranthene	2.43E-11	kg	3.01E-11	kg	
Benzo(a)pyrene	1.97E-11	kg	3.50E-11	kg	
Fluoranthene	2.22E-12	kg	3.93E-13	kg	
PAH, unspecified	4.69E-11	kg	1.43E-11	kg	

3.4 Road maintenance

The road maintenance process includes milling of 4 cm of the road surface and subsequent resurfacing of the road. Resurfacings is assumed to be the same process as asphalt laying and is discussed in the previous section. Data for road milling was obtained from Bartolozzi et al. (2012) who specify that milling a top layer with 4 cm thickness consumes 36 L/h at a capacity of 500 m^2/h. Particulate emissions from the road surface are taken from Stripple (2001). An overview of the values is given in Table 5.

Table 5: Road milling.

Parameter	**Asphalt rubber**		**Reference asphalt**		**Reference**
Reference product	*Value*	*Unit*	*Value*	*Unit*	
Milled road	1	m2	1	m2	
Inputs					
Miller (diesel), GLO	2.56	MJ	2.56	MJ	Bartolozzi, 2012
Transport (lorry), EURO6, EUR	4.91	t*km	5.14	t*km	Bartolozzi, 2012
Waste					
Inert waste, RoW	98.3	kg	103	kg	
Emissions					
Particulates (PM10)	4.4E-5	kg	4.4E-5	kg	Stripple, 2001

3.5 Road use

Potential emissions during road use are related to road wear, tire wear and fuel consumption as a function of road resistance. One way of distinguishing between the reference asphalt and asphalt rubber is by making use of the International Roughness Index (IRI). Jung et al. (2002) conclude that the IRI of asphalt rubber remains relatively constant over its lifetime, whereas the IRI of conventional asphalt increases with age. We have therefore opted to implement an IRI of 0.9 m/km for asphalt rubber and an IRI of 1.2 m/km for the reference asphalt.

Chatti and Zaabar (2012) provide a relationship between IRI and both fuel consumption and tire wear. For a medium-sized passenger vehicle driving at 88 km/h fuel consumption and tire wear increase by 1% for per 1 m/km increase in IRI. For the 0.3 m/km difference in IRI we can therefore assume a 0.3% change in tire wear and fuel consumption for vehicles between. This is implemented by adding 1200 km of personal car transport to the reference asphalt case, assuming average daily traffic of 10,000 cars per day.

Another potential source of emissions during road use stems from leaching of materials from the road asphalt materials. Data for Al and Hg was found in Azizian et al. (2003), but flows are little at 0.17 kg Hg and 14 kg Al over a 1 km stretch of road and a 40 year lifetime. In addition, a difference between the asphalt rubber and reference asphalt pavement could not be found, and leachate from the pavement during its lifetime is therefore not included in this analysis. The input and outputs to road use are summarized in Table 6.

Table 6: Road use.

Parameter	**Asphalt rubber**		**Reference asphalt**		**Reference**
Reference product	*Value*	*Unit*	*Value*	*Unit*	
Road use	1	unit	1	unit	
Inputs					
Transport, passenger car, EUR	0	km	1200	km	Jung, 2002 Chatti, 2012

4 Life Cycle Impact Assessment

This Chapter discusses the results of the life cycle impact assessment. From the available impact categories, the ones recommended in the product category rule for asphalt mixtures that was published earlier this year are reported (EPD International AB, 2018). In addition, particulate matter emissions are included as this is relevant to the debate around the emission of microplastics. Totals for the two cases are given in Table 7. What is immediately apparent is that the impacts are approximately 30% lower for the asphalt rubber when compared to the reference asphalt across all 8 presented impact categories. This can primarily be explained by two parameters in the LCI model: the lifetime estimates for the two different pavements and the thickness of the asphalt rubber layers compared to the reference asphalt. The amount of material processed for the reference asphalt is significantly higher due to the extra 5 cm layer in the model and the shorter service life of 6 years of the top layer requires 2 times more resurfacing over the 40-year lifetime of the road.

These results presented Table 7 are re-calculated for different functional units in Table 9 and Table 10 in the appendix of this report to facilitate comparison with other studies. The results are expressed in 240 m^2*yr (the functional unit used by Johansson (2018)), m^2*yr and m^2 with a service life of 40 years. Despite the inclusion of the asphalt laying, the results in this study are lower than those presented by Johansson (2018). For example, here we calculate life cycle greenhouse gas emissions of 394 kg CO_2-eq per 240 m^2*yr compared to a value of over 600 kg CO_2-eq per 240 m^2*yr reported by Johansson (2018). The difference here lies in the lifetime assumptions of the different models. Here, we use a 40 year service life as recommended by the product category rule for asphalt mixtures. Johansson (2018), takes a slightly different approach and, while including the lifetime of the asphalt (8.3 years for asphalt rubber) do not distribute the impacts associated with the binder course over the longer 40-year time period.

The influence of key parameters such as lifetime and number of asphalt layers on the model results is discussed in section 4.2. First, however, we present the contribution of individual processes to the impact category totals.

Table 7: Impact assessment results for 8 selected impact categories. Totals are expressed per functional unit of 1 km road, 7 m width, over the duration of 40 years.

Impact category	**Indicator unit**	**Asphalt Rubber**	**Ref. asphalt**	**Change**
Global warming potential (100 yr)	kg CO_2-eq	4.60E+05	7.04E+05	-35 %
Acidification potential	kg SO_2-eq	2.44E+03	3.60E+03	-32 %
Eutrophication potential	kg PO_4-eq	4.17E+02	6.32E+02	-34 %
Formation potential of tropospheric ozone	kg C_2H_4-eq	1.54E+02	2.23E+02	-31 %
Abiotic resources depletion potential	kg Sb-eq	8.72E+03	1.22E+04	-28 %
Fossil depletion potential	kg oil-eq	4.62E+05	6.44E+05	-28 %
Ozone depletion potential	kg CFC11-eq	2.31E-01	3.21E-01	-28 %
Particulate matter formation potential	kg PM10-eq	8.91E+02	1.35E+03	-34 %

4.1 Contribution analysis

Contribution analysis breaks down the total life cycle impacts presented in Table 7 by the direct and indirect contributions of the individual modelled foreground processes.

Figure 2 and Figure 3 show the contribution analysis results for the asphalt rubber and the reference asphalt. What is apparent is that the emissions from the production of bitumen are dominant for both asphalts. Other large contributors are the production of the asphalt, production of the aggregates as well as transport related to all the materials. The energy required for granulation of the ELTs appears in *Figure 2*, but only in the order of one percent. The fuel combustion processes dominate the impact categories, and very little effect stem from non-combustion related particulate matter emissions.

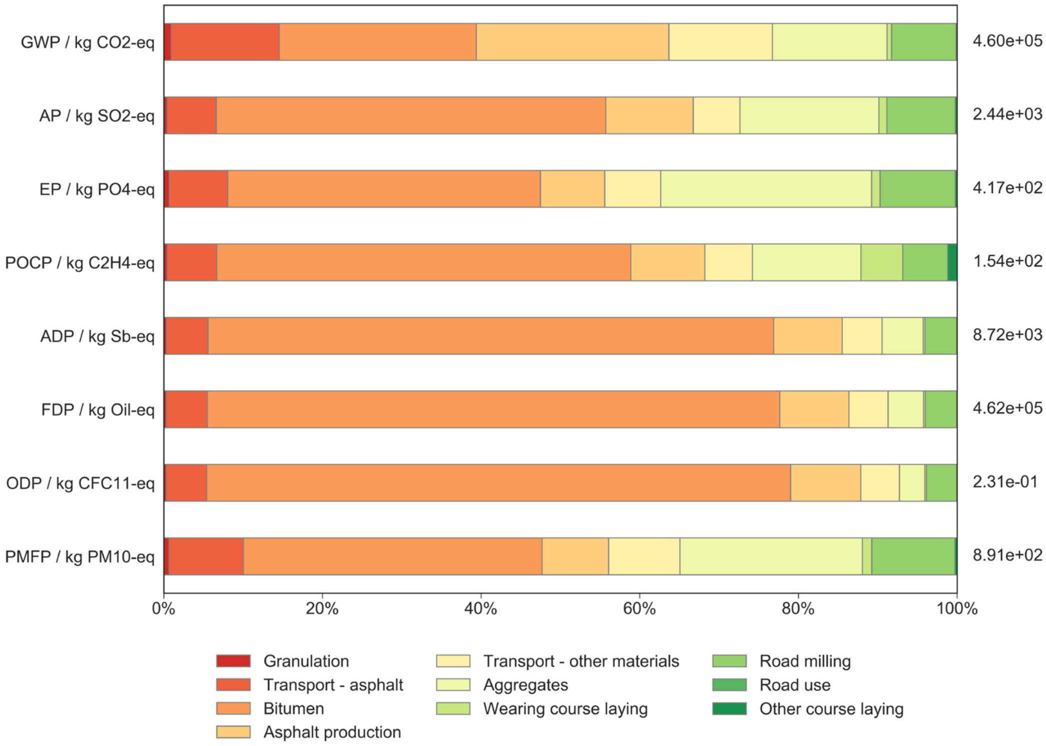


Figure 2: Contribution analysis – asphalt rubber. GWP – Global warming potential; AP – acidification potential; EP – Eutrophication potential; POCP - Formation potential of tropospheric ozone; ADP – Abiotic resources depletion potential; FDP – Fossil depletion potential; ODP – Ozone depletion potential; PMFP – Particulate matter formation potential

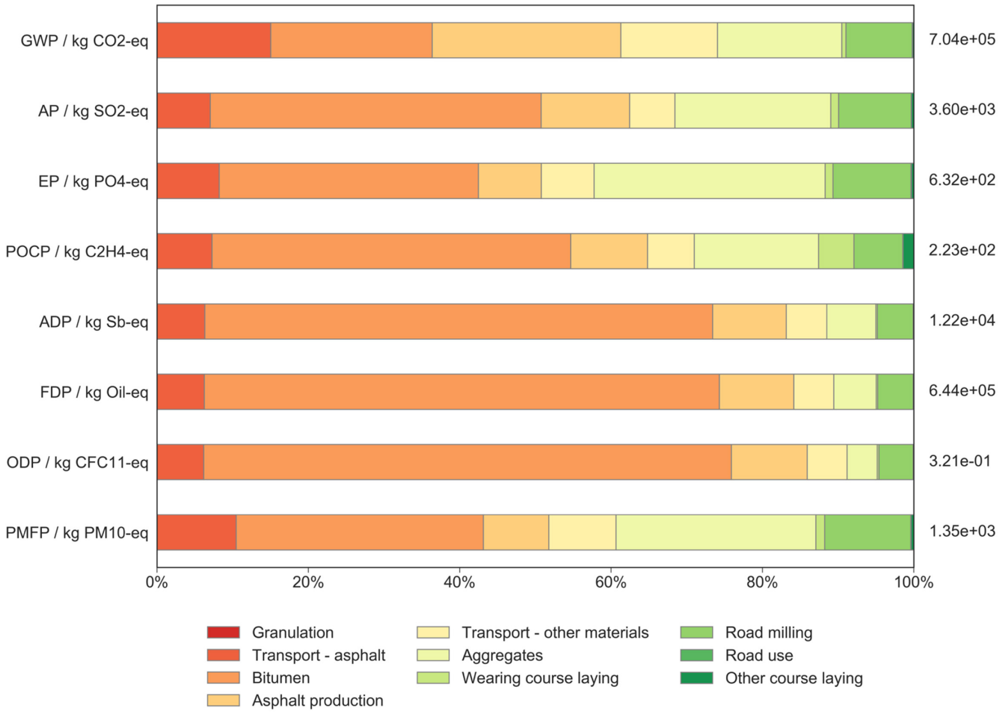


Figure 3: Contribution analysis – reference asphalt.

In addition to the analysing the contribution of different processes at the level of the modelled system, the impact assessment allows to calculate the contribution of individual environmental stressors, as a result of processes in the life cycle inventory database. These processes in turn are connected to the asphalt rubber life cycle. One way of visualizing these relationships including their relative magnitude for a single impact category is by using a Sankey diagram (Lupton and Allwood, 2017). An example of this is shown in Figure 4 and Figure 5 for the life cycle greenhouse gas emissions associated with the asphalt rubber and reference asphalt road. Stressors are shown on the left-hand side, background processes from the inventory database in the middle and the foreground system model on the right-hand side. All stressors and processes contributing more that 0.75% to the total of 0.46 Gg CO_2-eq per km road are individually included in this diagram. All other stressors and processes below this threshold are aggregated into the respective categories' other stressors, other background processes, and other foreground processes. Figure 4 shows that most of the global warming potential can be traced down to carbon dioxide and methane emissions. Large contributors in the life cycle are the combustion of light fuel oil in the production of asphalt (here labelled by the ecoinvent process name *heat, district or industrial, other than natural gas*) and the freight transport of the materials. As the modelled systems for both the asphalt rubber and reference asphalt road are largely the same, the diagrams in Figure 4 and Figure 5 are very similar.

In the Appendix the Sankey diagrams for particulate matter are included. Here, most of the particulate matter formation potential can be attributed to emission of nitrogen oxides and sulphur dioxide, as well as emission of particulates <2.5 µm and particulates with sizes between 2.5 µm and 10 µm. These emissions are caused mainly by diesel combustion processes, as well as the combustion of waste natural gas in a production flare as part of the bitumen production value chain.

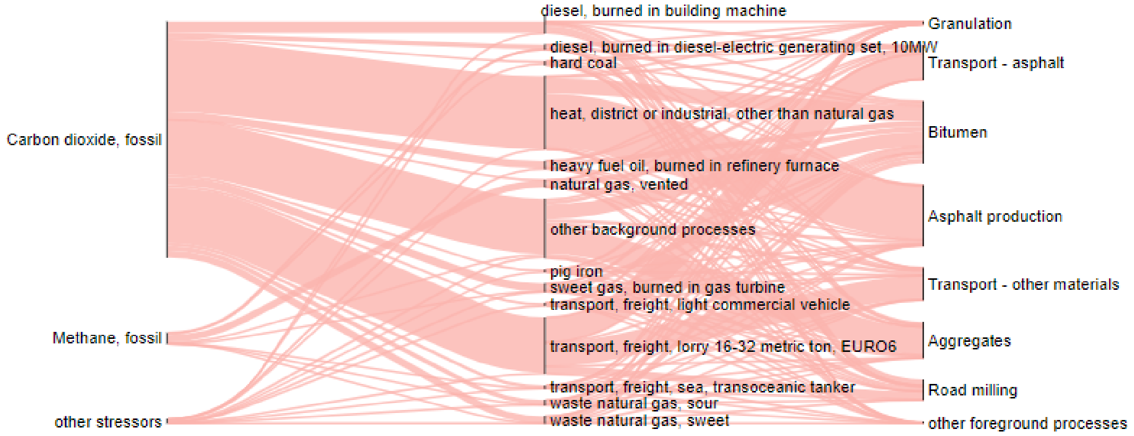


Figure 4: Sankey diagram of contribution of individual stressors and processes to greenhouse gas emissions with a cut-off of 0.75% for the asphalt rubber road.

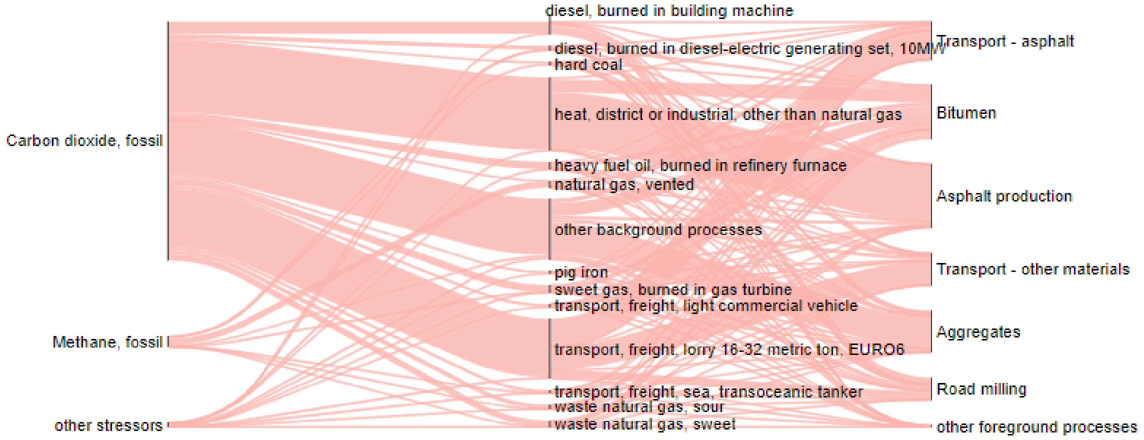


Figure 5: Sankey diagram of contribution of individual stressors and processes to greenhouse gas emissions with a cut-off of 0.75% for the reference asphalt road.

4.2 Key parameters for uncertainty analysis

In the following paragraphs, we will discuss selected key parameters for uncertainty analysis. Based on the results presented in Section 4.1, three uncertainty cases were selected to investigate the impact of key parameters on the life cycle impact assessment results. Firstly, in case U1 the lifetime assumption of the asphalt rubber road is decreased to 6 year, instead of the 9-year used in the base case presented before. Effectively, this implies that more resurfacing of the asphalt rubber top layer is required within the 40-year service life of the road, thus increasing both life cycle energy and material requirements. Secondly, in case U2 the number of asphalt rubber layers is increased from two to three, to match the number of layers in the asphalt reference case. Lifetime for the asphalt rubber top layer, however, is kept at 9 years. Thirdly, as asphalt production contributes up to a 25% to the life cycle impacts, we test the energy requirements and source for asphalt production in U3. Instead of requiring 0.304 MJ of light fuel oil (LFO) and 0.015 kWh of electricity per kg asphalt production, U3 increases LFO consumption to 0.527972 MJ and 0.005493 MJ natural gas per kg of asphalt production. These new values for energy consumption in asphalt production are now based on White et al., (2010), who report 24.6 L LFO and 0.269 m^3 natural gas per 2 short ton asphalt production, rather than Johansson (2018). The three cases are summarized in Table 8.

Table 8: Short description of the uncertainty cases.

Nr.	Parameter change
U1	Decrease lifetime of asphalt rubber road to 6 year.
U2	Increase layers of rubberized asphalt to same amount of asphalt as reference asphalt
U3	Different energy source and increased energy requirements for asphalt production

The life cycle impact assessment results for the three cases are shown in Table 11 in the Appendix. Here, the results are plotted against the reference asphalt for all impact categories in Figure 6. The uncertainty analysis shows that the lifetime of the asphalt rubber top layer is a crucial parameter in determining the life cycle impacts, as a decrease of the lifetime to 6 yr increases the impacts with approximately 40% to nearly the values of the reference asphalt. The effect of 3 layers of asphalt rubber, as opposed to 2 layers is smaller, though still a 20% increase in impacts is calculated. Shifting of energy source (electricity to natural gas) and increasing energy requirements while keeping lifetime of the top layer at 9 years and 2 pavement layers of asphalt rubber increases the GWP by 17% but other environmental impacts by approximately 6%. Conversely, decreasing the energy requirements for asphalt production has a positive effect on impact reductions.

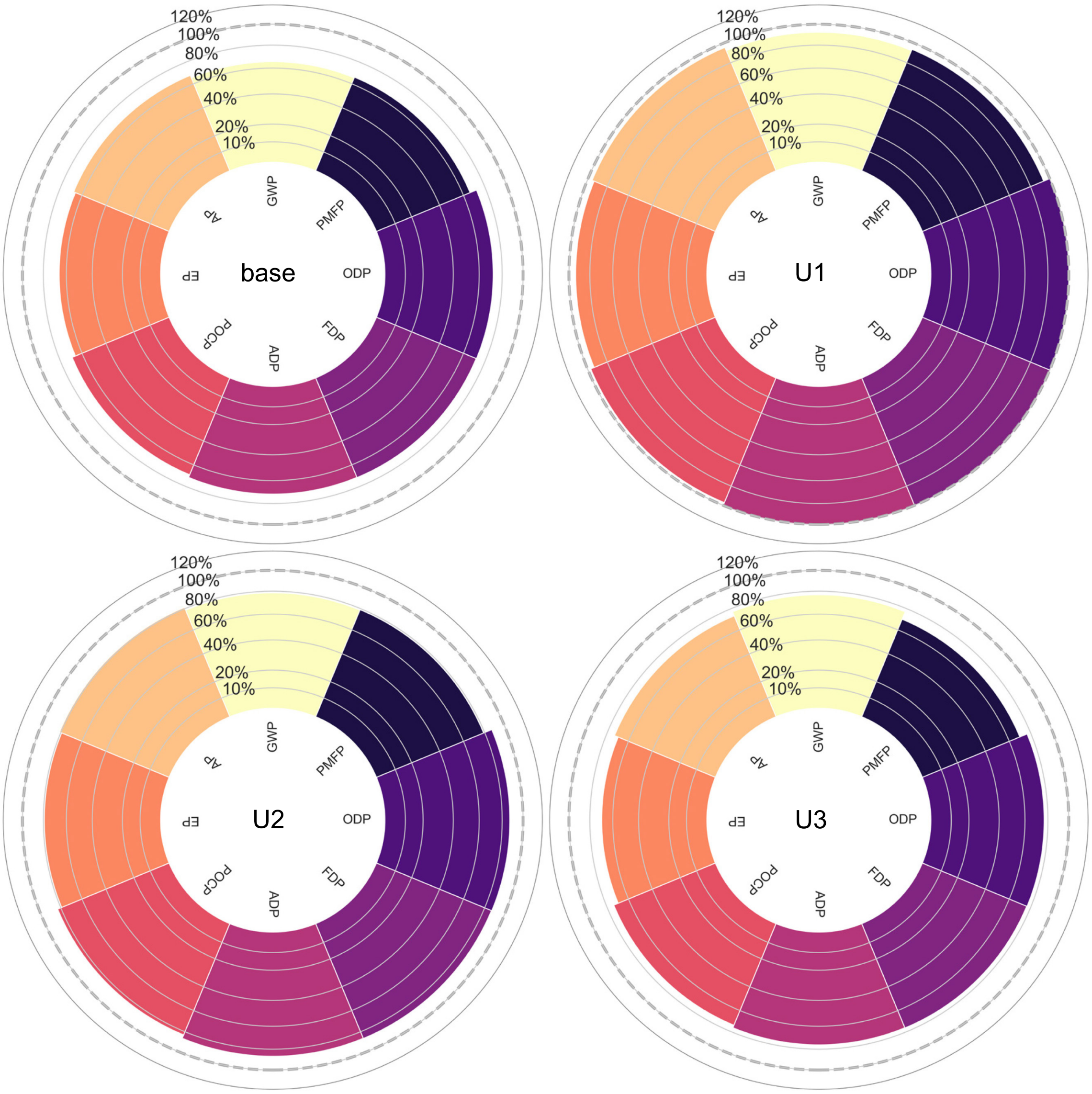
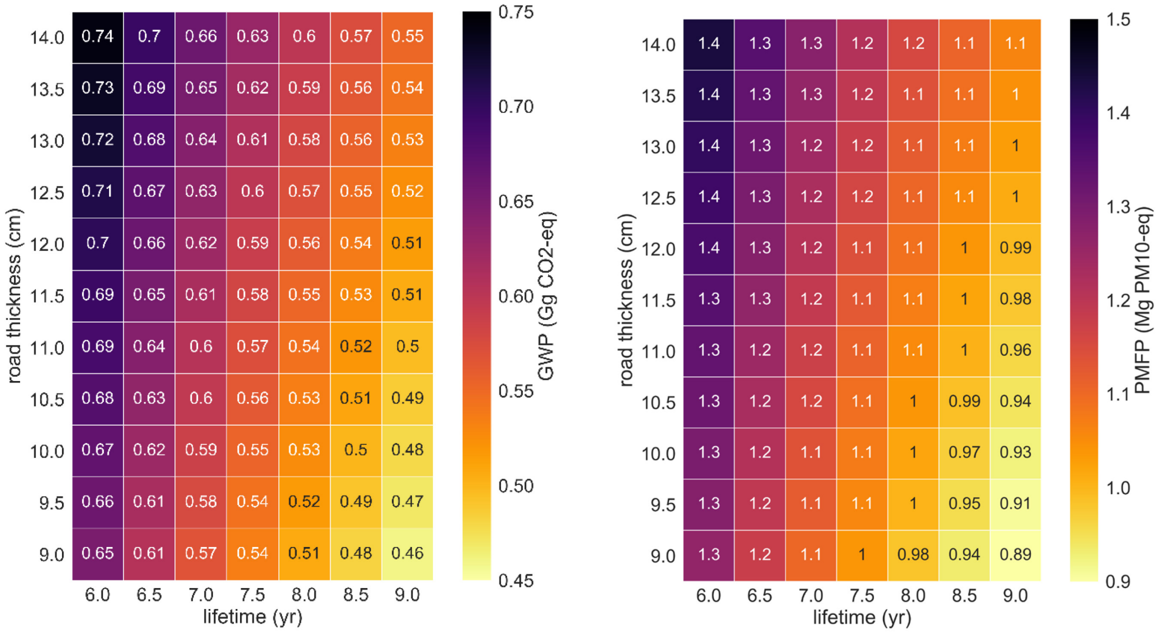


Figure 6: Impact for all impact categories relative to the reference asphalt road for the base case presented in this report and the three uncertainty cases outlined in Table 8.

To study in more detail the effects of service life of the top layer and the amount of asphalt required case U1 and U2 were combined. Impact assessment was carried out for asphalt rubber pavements where the service life was varied from 6 to 9 years and total layer thickness was varied between 9 to 14 cm. The results for greenhouse gas emissions and particulate matter formation are shown as a heat map in Figure 7. Figure 7 confirms that it is worth considering laying an extra asphalt rubber layer if this increases the service life of the top layer. For example, the impact values for a 9 cm (4 + 5 cm) configuration with a 6.5-year service life are considerably higher than for a 13 cm (4 + 4 + 5 cm) configuration with an 8.5-year service life.



road thickness (cm)	6.0	6.5	7.0	7.5	8.0	8.5	9.0
14.0	0.74	0.7	0.66	0.63	0.6	0.57	0.55
13.5	0.73	0.69	0.65	0.62	0.59	0.56	0.54
13.0	0.72	0.68	0.64	0.61	0.58	0.56	0.53
12.5	0.71	0.67	0.63	0.6	0.57	0.55	0.52
12.0	0.7	0.66	0.62	0.59	0.56	0.54	0.51
11.5	0.69	0.65	0.61	0.58	0.55	0.53	0.51
11.0	0.69	0.64	0.6	0.57	0.54	0.52	0.5
10.5	0.68	0.63	0.6	0.56	0.53	0.51	0.49
10.0	0.67	0.62	0.59	0.55	0.53	0.5	0.48
9.5	0.66	0.61	0.58	0.54	0.52	0.49	0.47
9.0	0.65	0.61	0.57	0.54	0.51	0.48	0.46

road thickness (cm)	6.0	6.5	7.0	7.5	8.0	8.5	9.0
14.0	1.4	1.3	1.3	1.2	1.2	1.1	1.1
13.5	1.4	1.3	1.3	1.2	1.1	1.1	1
13.0	1.4	1.3	1.2	1.2	1.1	1.1	1
12.5	1.4	1.3	1.2	1.2	1.1	1.1	1
12.0	1.4	1.3	1.2	1.1	1.1	1	0.99
11.5	1.3	1.3	1.2	1.1	1.1	1	0.98
11.0	1.3	1.2	1.2	1.1	1.1	1	0.96
10.5	1.3	1.2	1.2	1.1	1	0.99	0.94
10.0	1.3	1.2	1.1	1.1	1	0.97	0.93
9.5	1.3	1.2	1.1	1.1	1	0.95	0.91
9.0	1.3	1.2	1.1	1	0.98	0.94	0.89

Figure 7: Heat map of greenhouse gas (left) and particulate matter (right) emissions for 1 km asphalt rubber road for varying thickness and lifetimes. Note that the values in each cell are rounded, but the colour scale corresponding to the value is continuous.

PART II
PESTLE analysis

5 PESTLE methodology

Asphalt producers are part of an industry environment, consisting of suppliers, customers and competitors, all of which is shaped by certain factors that they cannot change themselves, i.e. external factors. PESTLE analysis provides a framework for analyzing the industry environment, identifying factors in key areas that have an impact on business operations. It originates from Francis Aguilar (1967) who discussed economic, technical, political and social factors impacting the business environment (Rastogi & Trivedi, 2016). There exist various forms of this analysis, including PEST, PESTLIED, STEEPLE, STEPE and more[1]. When analyzing the external factors of an industry or organization, one should choose the form that is the best fit for the industry or organization in question. Recognizing the need to include environmental and legal factors, we will analyze the external factors affecting the potential for rubber asphalt through PESTLE, which includes these key areas:

Political	Policies are important to keep track on, both current policies and the possibility for future changes. Therefore, one should consider upcoming elections, political trends, as well as the level of bureaucracy and political stability. Because of multinational organizations, global trade and alliances such as the European Union, one should also consider policies and policy changes outside the businesses' operating country.
Economic	Economic factors are important because they may affect the consumer's purchase power and demand for goods, or the company's purchase power. Such factors include interest rates, exchange rates, commodity prices, inflation and economic growth. Some industries are highly sensitive to changes in the national and global economy, while others are not as sensitive.
Socio-cultural	Socio-cultural factors are the cultural aspects, beliefs and attitudes that could affect consumption and demand for goods. It includes factors such as demographics, standard of living, population growth, consumer attitudes and the like. These may not be easy to predict but are still important.
Technological	These factors arise from technology developments. Industries relying on technology to operate should be aware of relevant technology developments, as it can change the way to operate, reduce costs or enhance the product quality. Some key words are R&D, technology transfer, failed projects, emerging technologies and patents.
Legal	Legal factors one should consider is the current and forthcoming legislations that may affect the industry, including health and safety, employment, import and export, technology standards, taxes and more.

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[1] The PEST framework assesses political, economic, sociological and technological factors in the industry environment. Other variations evolved from the PEST analysis. STEPE added ecological factors to the original framework, while STEEPLE added environmental, legal and ethical factors, and PESTLIED added legal, international, environmental and demographic factors.

	These should be considered not only for the operating country, but also other countries relevant for the industry.
Environmental	The industry’s impact on surrounding environment and greenhouse gases have gained increasing attention in the recent years, causing demands for sustainable resource use and environmentally friendly production. Consequently, one should consider factors such as environmental legislation, input and emission restrictions and waste management. In addition, climate change may impact the industry through natural disasters, changing weather conditions and cycles.

PESTLE is a systematic approach that includes key areas, which makes it well suited for scanning the industry environment. Its straightforward and simple nature allows it to be used in workshops and groups consisting of individuals that have little experience from strategy planning. Thus, it allows for representatives with different functions and background to take part in the work and complement each other with their specialties. The focus should be on *identifying* the relevant factors when using PESTLE, and then rate the importance of each factor. Information gathered through PESTLE and other industry analysis frameworks would be useful to predict future barriers and opportunities.

There are some implications that one should be aware of when conducting a PESTLE analysis. First, the framework treats every factor independently, even though some factors might be linked. Researchers have developed models to overcome these limitations (Ho, 2014; Yüksel, 2012). Second, some factors may fit into several areas. In such cases, one should keep in mind the purpose of the PESTLE analysis – to identify factors that could affect the industry. Third, important information and factors could easily be missing, as the analysis is dependent on the knowledge from attending representatives. Finally, other frameworks should be applied to get the full picture of the business environment, as PESTLE only support analysis of external factors, i.e. factors that none of the suppliers, customers and competitors within an industry have the power to influence. One example is Porter’s five forces of competition framework who focus on the rivalry among existing firms, threat of new entrants, substitutes, as well as the bargaining power of suppliers and buyers (Grant & Jordan, 2015).

In this study, the PESTLE analysis was based on the discussions under two different stakeholder workshops carried out in the autumn of 2018 gathering the feedback from experts at Veiteknisk Institutt, Statens Vegvesen and Veidekke AS.

6 Results from the PESTLE analysis

6.1 Political

Current policy for waste management focus on waste as resources and circular economy. The legislation states that scrap tires shall be recycled. The main use of scrap tires has been energy recovery (73 %), while the remaining tires are utilized through material recovery (23 %) and reuse (4 %) (Dekkretur, 2018). Rubber granulates from scrap tires are used in artificial turfs, trotting tracks, noise embankment along roads among other. Unlike several other countries, there is no targeted policy for rubber asphalt in Norway. However, this might change as microplastic emissions from the road sector and artificial turfs have recently gained increased attention from the media and politicians. In fact, emissions of microplastics from especially tires is addressed in several White Papers, both with regards to waste management and transport (St.Meld. 45 (2016-2017), National Transport Plan 2018-2029 (St.Meld. 33 (2016-2017)). Although there have been some studies on microplastic emissions in the transport sector, there is lack of evidence regarding emissions from rubber asphalt compared to polymer-modified asphalt and traditional asphalt.

There is an ongoing effort to reduce greenhouse gas emissions in the transport sector. In fact, the Ministry of Transport and Communications are developing an action plan for fossil-free construction sites in the transport sector (St.Meld. 33 (2016-2017)). Environmental Product Declaration (EPD) have been applied by the sector as documentation of CO_2 emissions associated with the projects. These are based on life cycle analysis (LCA) and conforming to international standards. The Norwegian Public Roads Administration (NPRA) currently work on pilot projects using allotment criteria, bonus schemes and requirements to reduce CO_2 emissions on construction sites, in which EPDs are implemented. Unfortunately, the existing EPDs only include the measures from the production stage of asphalt and end life (waste). It does not consider durability and measures from the use stage.

Some of the participants on the workshop pointed out that rubber asphalt has been tested on Swedish roads for a long time. However, this has not resulted in any significant use of rubber asphalt. The reason is not clear but could be due to problems with smell when rubber asphalt first was introduced in Sweden, as well as lacking policies supporting rubber roads. This expression of skepticism could be reasonable, but it could also be based on outdated knowledge or wrong information. The skepticism could be a barrier for introducing rubber asphalt to Norway, which could be solved through pilot projects built on existing knowledge from other countries.

Although rubber asphalt has several advantages, it seems like the road industry are reluctant or lack incentives to apply it on Norwegian roads. That being said, discarded tires are ultimately the tire producers' and importers' problem, and not the road industry's responsibility. However, recycling of waste tires can also be a social problem and responsibility which need to be solved by collaboration between different parties

6.2 Economic

The oil price is an important factor for both the waste industry and asphalt industry. Production costs of asphalt are known to increase whenever the oil price increase. Consequently, changes in oil prices are accounted for in the contracts. The asphalt industry's sensitivity to oil prices suggest that the asphalt industry would demand more rubber from scrap tires in periods of high oil price, if total costs associated with rubber asphalt are below that of traditional asphalt. At the same time, the waste industry already experiences higher demand for reclaimed tires whenever the oil price increase.

Each year hundred thousand tons asphalt waste are generated from construction. The industry utilizes recycled asphalt in production to combat the vast amount of waste. Used asphalt are generally considered as a resource by the industry, not waste. The annual recycle rate are usually 95-100 % (KFA, 2018; SSB table no. 09781). Unfortunately, asphalt is also discarded at illegal landfills (KFA, 2018). The industry is not obligated to reuse or recycle used asphalt, but discarded asphalt must be deposited at a landfill if it is not recycled (KFA, 2016). Thus, an economic factor would be any costs incurred due to reduced recyclability of asphalt, e.g. additional material costs and costs related to discarding asphalt at landfills. According to the national action plan for construction waste, the costs related to landfills (at the time of their report) were sufficiently large to motivate the industry to avoid landfilling by deposit the asphalt at temporary storage houses for recycling (NHP network, 2007). It should be noted that crumb rubber modified asphalt have been recycled in the US (Wu et al., 2015).

Subsidies and fees could be useful to give incentives towards the use of rubber asphalt in construction. The NPRA have previously given bonus to those who used low temperature asphalt (LTA) (Bragstad et al., 2014). Similar subsidy schemes could be implemented for rubber asphalt, or even based on (low) CO_2 emissions (taking into account the expected durability of rubber asphalt compared to normal asphalt), and the subsidy size should be of sufficient size to give incentives towards switching technology. The NPRA currently assess the option to demand emission cuts and climate-friendly solutions in contracts or prioritize it through allotment criteria. Some of the workshop participants emphasized that non-priced values such as benefits in health, CO_2 emissions and noise ought to be valued in monetary terms.

6.3 Socio-cultural

There have been increasing focus on reuse and recycling in recent years, and people's attitudes have changed accordingly. Producers could take advantage of this trend by utilizing scrap tires in asphalt production, and market their products as sustainable or the like. On the other hand, it could be a disadvantage for producers that cannot produce rubber asphalt or fail to deliver sufficient amounts to their customers in times of high demand.

Oslo municipality won the European Green Capital award for 2019 and are a forerunner in their work with environmental concerns. They cooperate with the NPRA, resulting in new contracts with suppliers that emphasize function and quality including reduced environmental impact. It could be a driving force for the asphalt industry to offer good and more environment friendly products and give incentives to invest in rubber asphalt.

Again, rubber asphalt is a solution for the tire industry's waste problem. Recycling of waste can also be a societal problem and responsibility. Subsidies may be important to give the asphalt industry incentives to produce rubber asphalt, thus help solve a societal problem. The use of rubber asphalt may face opposition from the society provided if the asphalt cannot be recycled. Therefore, it is important to enable recycling of rubber asphalt.

6.4 Technological

Smell and recyclability of rubber asphalt were the main concerns emphasized by the workshop participants. It will be crucial to reduce or eliminate the smell of rubber. Some of the participants mentioned the possibility to use chemicals that reduce smell, but they did not recommend it as it could affect health of workers or require added health, safety and environment (HSE) measures. Another option would be to reduce the temperature, which is possible. The third option was to pave asphalt in closed facilities to avoid smell in the surrounding environment, but it does not solve issues with smell for the workers. Also, the latter option was considered very costly, and most likely unrealistic.

About 100 % of discarded asphalt are recycled in production of new asphalt. The participants did not know whether demolished rubber asphalt could be recycled. They seemed reluctant to implement rubber asphalt if it reduced the recycling of old asphalt. Again, they argued that discarded tires are ultimately the tire producers' and importers' problem, and not the road industry's responsibility. Consequently, if rubber asphalt were to be used in Norway, tire producers should take responsibility for developing environmentally friendly tires suitable for recycling rubber asphalt. As mentioned, crumb rubber modified asphalt have been recycled in the US, but further research is required (Wu et al., 2015).

With regards to technology switch from traditional to rubber asphalt production, the participants briefly mentioned that rubber asphalt require:

- higher temperature than asphalt produced in Norway these days, and
- a homogenous, stable binder between rubber and bitumen.

They did not elaborate these statements. The asphalt industry seems to be satisfied with the type of asphalt they produce today. Any technology switch is associated with risk of producing inferior or more costly products.

The participants appeared to be encouraged by the benefits of rubber asphalt such as longer lifetime and the prospect of building thinner layers, found in Ragnsells' study (Johansson, 2018). These factors could enable producers to reduce material use, thus costs and CO_2 emissions. There was consensus that the road sector needs well-documented information about benefits and implications of rubber asphalt before implementing the technology in Norway. Some argued that the technology should be tested and documented in Scandinavian/Norwegian climate, while others argued that existing experience in other countries would be enough. Either way, there is need for further research.

6.5 Environment

The overall impression was that the participants in general lacked knowledge about rubber asphalt and its impact on the environment. Still, they succeeded in identifying potential environmental factors, but could not conclude whether these represented threats or opportunities for the use of rubber asphalt in Norway. They had a good overview over politics and legislation concerning environmental effects, which are described in previous sections.

Rubber asphalt could lessen road noise compared to traditional asphalt, because of its softer road surface. But soft road surfaces are also known to generate more road dust. Asphalt roads in Norway emit harmful chemical substances into the environment today. The workshop participants emphasized the need to compare emissions from all relevant types of asphalt, including rubber asphalt and PMB asphalt. Depending on the result, emissions from rubber asphalt could either represent an opportunity or threat for the use of rubber asphalt in Norway.

The workshop participants were also concerned about smell, although there exists technology that reduce smell in production of rubber asphalt. Some argued that the opinions of a few prominent persons are being heard, which could affect adoption of new technologies, such as rubber asphalt, as well as the reputation of products. Microplastics and recycling have gotten increasing attention by the general public and politicians, out of concern for the environment. On one hand, if these persons promote recycling and circular economy, it could benefit the use of rubber asphalt. On the other hand, these people could also highlight environmental concerns related to microplastics, which could threat the use of rubber asphalt.

6.6 Legal

Norwegian legislation promotes recycling of reclaimed tires. Landfilling of scrap tires are not allowed in Norway, according to the Waste Regulations[2]. Instead, scrap tires must be utilized for material recycling, energy recovery or reuse, which are tire producers and importers' responsibility.

Asphalt producers and the construction industry must comply with several laws and regulations. Some of these might be of importance for the use of rubber asphalt. For instance, the Pollution Act and Pollution Regulation. The latter has several provisions regarding dust, odor and noise for asphalt plants[3]. The legislation related to health and security may also be of importance. The Working Environment Act emphasize the importance of limiting health risks for workers. For instance, by requiring companies to replace chemical and biological materials that could pose a health risk for workers with less dangerous materials and processes[4].

Regarding current legislation, any barriers to the use of recycled tires in asphalt production will probably be related to odor or safety for workers. However, there are disagreements whether odor could be reduced to an acceptable level using best available technology.

The Public Procurement Act and associated regulations are also of relevance for rubber asphalt, due to the amount of asphalt requested by public sector. The law states that the public sector must use procurement practices that help reduce negative environmental effects and choose climate-friendly solutions when appropriate[5]. Consequently, the public sector can set requirements relating to effects on climate and environment in procurements, or otherwise prioritize offers with less impact on climate and environment[6]. This is relevant for rubber asphalt as its carbon footprint might be less than traditional asphalt throughout the production *and* user stage, according to a Swedish study (Johansson, 2018). Thus, rubber

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[2] The Waste Regulations chapter 5

[3] The Pollution Regulation chapter 24

[4] The Working Environment Act § 4-5

[5] The Public Procurement Act § 5

[6] Anskaffelsesforskriften § 7-9

asphalt may have an advantage if the public sector requires or prioritize low CO_2 emissions in procurement.

The analysis of legal factors does not indicate any limitations for reuse of discarded tires in asphalt production. On the contrary, recycling of scrap tires is mandatory for the tire producers and importers, and rubber asphalt may have an advantage in procurements that emphasize emission reductions.

PART III

Discussion and conclusions

7 Discussion and conclusions

A screening LCA study was carried out here to compare the environmental impacts from asphalt containing 20% rubber in the bituminous binder - asphalt rubber - with conventional asphalt. The study incorporated both the production of the asphalt mix, subsequent laying of the asphalts, resurfacing the roads after the service life of the asphalt, as well as the difference between emissions from transport during road use.

Clear environmental benefits associated with asphalt rubber with respect to conventional asphalt were quantified. This is, however, subject to a range of assumptions on the behavior of specifications of conventional asphalt and asphalt rubber. One key parameter here is the service life assumption of the top asphalt layer, as this will influence the necessity and frequency of removing the top layer and resurfacing the road, both processes which cost significant amounts of energy and resources. Other parameters relate to the required amount and thickness of asphalt layers (2 or 3), as well as the fuel source and energy required for production of the asphalt mix. These parameters were investigated as part of an uncertainty analysis for this LCA. The analysis showed that increase in the service life of the top layer has the largest effect and can even compensate for additional impacts caused by switching from a two to three-layer system. Roads constructed with asphalt rubber are reported to have a longer service life that conventional roads. However, the evidence for this is scattered around case studies in various countries and seems to be mainly the result of assumptions or road engineering models of varying sophistication, rather than experimental verification. It is therefore unsure whether asphalt rubber in Norwegian conditions can achieve the expected increase in service life, before milling and resurfacing the top layer. Experimental verification of service life for a specific Norwegian road is therefore recommended for future studies.

Another area that requires further attention is the evaluation of the environmental impacts related to road use. In our LCA, the environmental impacts related to road use are negligible, but these effects are probably underestimated in the current study. This is because the amount of particulate matter and fuel consumption, when attributed to road use, is substantial, but is not included in our LCA comparative analysis. Normally, these emissions would be included as part of the vehicle transport emissions. The present analysis does account for differences in surface roughness between the two asphalts, but this difference is small enough to be neglected. However, specific Nordic conditions, such as driving with studded car tires, are not included in the analysis, though the question remains whether there will be significant differences between asphalt rubber and conventional asphalt in road abrasion.

Leaching of pollutants from the asphalt layer, as well as emissions of VOCs and PAHs during the laying of the asphalt, were found to be small compared to the emissions resulting from the combustion of fossil fuel in construction and plant equipment. However, the knowledge base is sparse as most studies focus on short term pollutant concentrations from the perspective of occupational health hazards. The same applies to the emissions of micro-plastics. Although we envisaged initially to include these effects in the current LCA comparison, documentation and reference data was missing at the time of the study. The question remains whether there will be significant differences between asphalt rubber and conventional asphalt in road abrasion, leaching and the production of micro-plastics.

A third aspect to be considered in future studies is noise. Beyond the current LCA study, asphalt rubber has been reported to have significant noise reduction capacities. In urban settings and along highways noise has, after air pollution, a significant impact on health. Future studies for Norway should include such a perspective.

In our PESTLE, we found no legal or political factors that explicitly prevent the asphalt industry from utilizing rubber granulates from reclaimed tires in asphalt production. In fact, recycling is encouraged both in Norwegian politics and legislation. However, while the tire recycling industry is generally positive to the disposal of used tires in asphalt production, additional incentives need to be put in place for the Norwegian asphalt producers to consider actively contributing to this development.

Main concerns by asphalt producers were related to smell, micro-plastic emissions and recyclability of rubber asphalt. Moreover, the industry currently focusses on low temperature asphalt (LTA) and reduction in CO_2 emissions. These factors should be addressed in further research on rubber asphalt, and possibly tested on Norwegian roads.

Our overall conclusion from the stakeholder consultation workshops is that the introduction of rubber asphalt would require a significant change in perception on the features of rubber asphalt, its technology advantages and recycling capabilities by asphalt producers and road owners. Research and pilot projects should be encouraged to enhance the knowledge about rubber asphalt and its characteristics through actual testing of rubber asphalt under Norwegian conditions. Furthermore, economic incentives and requirements in contracts might be vital for the adoption of rubber asphalt in Norway.

We trust that the knowledge gaps identified during this feasibility study form the basis for further research initiatives to motivate the Norwegian asphalt industry, tire recycling companies and road owners to develop sustainable rubberized asphalt solutions and to reduce the environmental footprint of road construction and use.

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Appendix A

A.1 LCA results expressed in different functional units

To facilitate comparison of the results of this study with other studies, the following tables provide the impact assessment results for various functional units. The base functional unit in this study is a 1 km road of 7 m width with a service life of 40 years. In Table 9 and Table 10 results are also expressed in 240 m^2*yr (the functional unit used by Johansson, 2018), m^2*yr and m^2 with a service life of 40 years.

Table 9: Impact assessment results for the asphalt rubber road expressed in various functional units.

Indicator	unit	km road	240 m^2*yr	m^2*yr	m^2
GWP	kg CO_2-Eq	4.60E+05	3.94E+02	1.64E+00	6.57E+01
AP	kg SO_2-Eq	2.44E+03	2.09E+00	8.70E-03	3.48E-01
EP	kg PO_4-Eq	4.17E+02	3.58E-01	1.49E-03	5.96E-02
POCP	kg C_2H_4-Eq	1.54E+02	1.32E-01	5.49E-04	2.20E-02
ADP	kg Sb-Eq	8.72E+03	7.47E+00	3.11E-02	1.25E+00
FDP	kg oil-Eq	4.62E+05	3.96E+02	1.65E+00	6.60E+01
ODP	kg CFC-11-Eq	2.31E-01	1.98E-04	8.26E-07	3.30E-05
PMFP	kg PM10-Eq	8.91E+02	7.64E-01	3.18E-03	1.27E-01

Table 10: Impact assessment results for the reference asphalt road expressed in various functional units.

Indicator	Unit	km road	240 m^2*yr	m^2*yr	m^2
GWP	kg CO_2-Eq	7.04E+05	6.03E+02	2.51E+00	1.01E+02
AP	kg SO_2-Eq	3.60E+03	3.09E+00	1.29E-02	5.14E-01
EP	kg PO_4-Eq	6.32E+02	5.42E-01	2.26E-03	9.03E-02
POCP	kg C_2H_4-Eq	2.23E+02	1.91E-01	7.96E-04	3.18E-02
ADP	kg Sb-Eq	1.22E+04	1.04E+01	4.35E-02	1.74E+00
FDP	kg oil-Eq	6.44E+05	5.52E+02	2.30E+00	9.21E+01
ODP	kg CFC-11-Eq	3.21E-01	2.75E-04	1.15E-06	4.59E-05
PMFP	kg PM10-Eq	1.35E+03	1.16E+00	4.82E-03	1.93E-01

A.2 Sankey diagrams for Particulate matter emissions

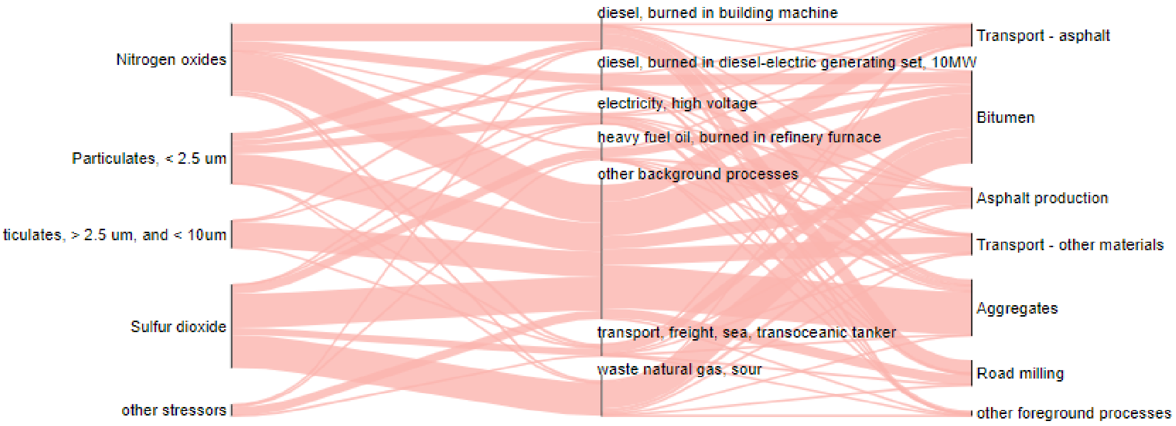

Figure 8: Sankey diagram of contribution of individual processes to particulate matter emissions with a cut-off of 3% for the asphalt rubber road.

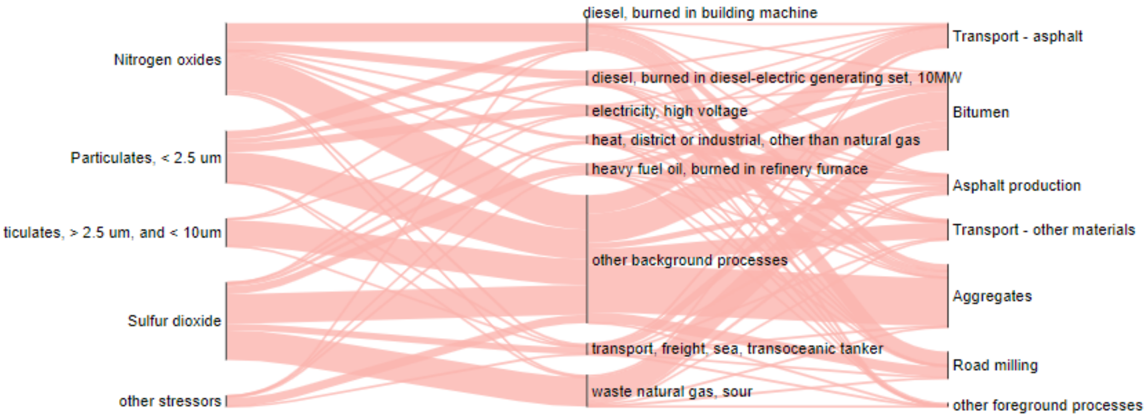

Figure 9: Sankey diagram of contribution of individual processes to particulate matter emissions with a cut-off of 3% for the reference asphalt road.

A.3 LCA results for the three uncertainty cases.

Table 11: Life cycle impact assessment results for the base case and uncertainty cases.

Indicator	unit	base	U1	U2	U3
GWP	kg CO_2-Eq	4.60E+05	6.49E+05	5.52E+05	5.40E+05
AP	kg SO_2-Eq	2.44E+03	3.44E+03	2.92E+03	2.63E+03
EP	kg PO_4-Eq	4.17E+02	5.90E+02	5.00E+02	4.38E+02
POCP	kg C_2H_4-Eq	1.54E+02	2.16E+02	1.85E+02	1.64E+02
ADP	kg Sb-Eq	8.72E+03	1.22E+04	1.06E+04	9.27E+03
FDP	kg oil-Eq	4.62E+05	6.47E+05	5.59E+05	4.91E+05
ODP	kg CFC-11-Eq	2.31E-01	3.24E-01	2.80E-01	2.46E-01
PMFP	kg PM10-Eq	8.91E+02	1.26E+03	1.07E+03	9.41E+02

A.4 Framework

	Current situation/ potential factors	**Opportunities**		**Threats**		**Solution**
		Waste industry	**Asphalt industry**	**Waste industry**	**Asphalt industry**	
Politics						
Economic						
Socio-cultural						
Technology						
Legal						
Environmental						

A.5 Workshop participants

Table 12: The workshop participants are employed in these companies and organizations.

Company/organisation name	**Description**
Veiteknisk institutt	A center of expertise on R&D, quality control and documentation of asphalt.
Kontrollordningen For Asfaltgjenvinning (KFA)	KFA is a voluntary industry association that promote and monitor recycling of reclaimed asphalt.
Directorate of Public Roads	Public body responsible for planning, construction and maintaining national and county roads.
NPRA Region South	Department under the Norwegian Public Roads Administration, responsible for planning, construction and maintaining public roads in five counties.
Nye Veier AS	State-owned company responsible for planning, construction and maintaining Norwegian highways.
Norsk Dekkretur AS	Norsk Dekkretur is responsible for *ensuring* that reclaimed tires are collected and recycled, on behalf of tire producers and importers in Norway.
Ragn-Sells Tyre Recycling	A waste and recycling company that collect and recycle reclaimed tires on mandate from Norsk Dekkretur. The participants were employed at the Swedish division.

Norsk institutt for luftforskning
Norwegian Institute for Air Research

NILU – Norwegian Institute for Air Research

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