TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

CARBON FOOTPRINT CALCULATION OF OIL SHALE ASH APPLICATION IN ROAD CONSTRUCTION

SÜSINIKU JALAJÄLJE ARVUTAMINE PÕLEVKIVITUHA KASUTAMISEL TEEDEEHITUSES

MASTER THESIS

Student: Anirudh Ramesh

Student code: 194381EABM

Supervisor: Dr. Viktoria Voronova, Sr. Lr.

Co-supervisor: Mrs. Arina Szczygielska,

Tallinn 2021

AUTHOR'S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

23.07.2021

Author: Anirudh Ramesh

Thesis is in accordance with terms and requirements

“.......” .... 20….

Supervisor: …........................
/signature/

Accepted for defence

“.......”....................20… .

Chairman of theses defence commission: ....
/name and signature/

Non-exclusive Licence for Publication and Reproduction of GraduationTthesis[1]

I, Anirudh Ramesh (name of the author) (date of birth: 13.04.1995) hereby

1. grant Tallinn University of Technology (TalTech) a non-exclusive license for my thesis Carbon Footprint Calculation of Oil Shale Ash Application in Road Construction,

supervised by Dr. Viktoria Voronova and

Co-supervised by Mrs. Arina Szczygielska

1.1 reproduced for the purposes of preservation and electronic publication, incl. to be entered in the digital collection of TalTech library until expiry of the term of copyright;

1.2 published via the web of TalTech, incl. to be entered in the digital collection of TalTech library until expiry of the term of copyright.

1.3 I am aware that the author also retains the rights specified in clause 1 of this license.

2. I confirm that granting the non-exclusive license does not infringe third persons' intellectual property rights, the rights arising from the Personal Data Protection Act or rights arising from other legislation.

---

[1] *Non-exclusive Licence for Publication and Reproduction of Graduation Thesis is not valid during the validity period of restriction on access, except the university`s right to reproduce the thesis only for preservation purposes.*

23.07.2021

Department of Civil Engineering and Architecture

THESIS TASK

Student: Anirudh Ramesh, 194381EABM

Study programme: EABM, Environmental Engineering and Management

main speciality:

Supervisor: Senior Lecturer, Viktoria Voronova

Consultants: Arina Szczygielska, Eesti Energia, arina.szczygielska@gmail.com

Thesis topic:

(In English) Carbon Footprint calculation of oil Shale ash application in road Construction

(In Estonian) Süsiniku jalajälje arvutamine põlevkivituha kasutamisel teedeehituses

Thesis main objectives:

1. The Estimation of the carbon footprint created by the application of OSA in road construction.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Completing the literature review and Introduction	17.06.2021
2.	The methodology section was written and OpenLCA was used	20.06.2021
3.	Writing the results based on the OpenLCA and finishing the final thesis version	10.07.2021

Language: English **Deadline for submission of thesis:** 23.07.2021

Student: Anirudh Ramesh 23.07.2021

/signature/

Supervisor: ………………… …………………….. "……."………………….20….a

/signature/

Consultant: ………………… ….………………….. "……."………………….20….a

/signature/

Head of study programme: …………… ………………… "……."………………….20…..a

/signature/

Terms of thesis closed defence and/or restricted access conditions to be formulated on the reverse side

CONTENTS

FIGURES

TABLES

PREFACE

This thesis is the final proof of competence for obtaining a Master of Science (MSc) degree in Environmental Engineering and Management from Tallinna Tehnikaülikool (TalTech), Estonia. This thesis was compiled in Estonia under the expert supervision of Dr. Viktoria Voronova, senior lecturer at TalTech and co-supervised by Mrs. Arina szczygielska, Eesti Energia from February 2021-August 2021.

The thesis was undertaken as part of Eesti Energia's project where Oil Shale Ash was used for the construction of a particular stretch of road in the western part of Estonia. The topic of the thesis, its aim and its research question were formulated together with my supervisor and my co-supervisor. As someone from a non-civil background, the research proved challenging initially but extensive investigation and study helped me answer the question that this thesis intended to show. The carbon footprint of oil shale ash application in road construction was ultimately estimated.

I would like to take this opportunity to thank my supervisor and co-supervisor for their patience and cooperation throughout the process of writing this thesis. Their critical reviews, valuable comments and suggestions at every step over the course of writing the thesis greatly helped me compile this well-researched study. I would also like to thank my sister for her continued encouragement and tips in writing this master thesis. I thank my parents for constantly keeping a check on me during the entirety of this thesis.
I also benefitted from debating and discussing issues with my friends.

Anirudh Ramesh,
July 2021

List of Abbreviations

CE	Circular Economy
CFBC	Continuous Fluidised Bed Combustion
EC	European Commission
ECRPD	Energy Conservation in Road Pavement Design and implementation
EU	European Union
EU-WFD	European Union-Waste Framework Directive
FU	Functional Unit
GHG	Green House Gases
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MPD	Modified Proctor Density
NCEP	National Energy and Climate Plan
OSA	Oil Shale Ash
OS	Oil Shale
PF	Pulverised Fired boiler
PM	Particulate Matter
PP	Power Plant
SPD	Standard Proctor Density

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) is the leading authority governing and setting standards for curbing and controlling the effects of climate change, global warming and carbon emissions [1]. Since the 1950s, there has been a significant increase in the global carbon emissions. About 43% of these overall emissions were from the industrial sector in 2020 [2].

As per the European Commission's (EC) 2019 report, 36% of the overall CO_2 emitted was from the construction sector [3]. Estimating the carbon footprint of every activity therefore, is vital in curbing its harmful after-effects. The transportation sector is the third highest emitter of carbon to the atmosphere with an overall percentage of about 22% [2].

The 2016 Paris Agreement laid down the norms to prevent carbon emissions from exceeding the set limits to meet both, the 2° C and the 1.5° C targets. These have been laid down for the next century [4], [5].The EU charted out energy conservation policies and goals in 2015. This gave the member states the opportunity to judiciously utilise safe, sustainable and affordable energy sources.

It also included renewable energy sources wherever possible [6]. So, countries that were heavily dependent on fossil fuel incineration had to cut down on their carbon emissions and adopt more sustainable practises. Thus, the EU introduced the concept of decarbonisation to meet the requirement to reduce carbon emissions from such member states. This was done by the formation of the *"Energy Union"* which marked another step towards a lower-carbon economy and smoothening the transition towards a sustainable circular economy [6].

Oil Shale (OS) in Estonia is the primary source of electricity, heat and oil generation in the region [6], [7]. In addition to significantly contributing to atmospheric carbon through fuel incineration, abundant dumping of spent calcareous Oil Shale Ash (OSA) to ash landfills introduces shortcomings pertaining to EU's Circular Economy (CE) and long-term sustainability targets [7].

Emissions in the form of heavy metal toxins elements such as Zn, As, Zr, Cd, Pb, etc from these landfills are an imminent threat to the surrounding environment [7]. Hence, it is of utmost importance to properly utilise OSA [6].

OS is a lower-calorific value fossil fuel that is calcareous in nature and rich in mineral content [7], [8]. Mostly comprised of carbonates, silicates and sulphides, the *Kukersite* type of OS is what is found in abundance in Estonia.

Quantities of about 3% Dolomite, 8% of Quartz, 65% calcite and trace amounts of other essential minerals constitute the Estonian OS [8]. In Estonia, the Circulating Fluidized Bed Combustion (CFBC) type of boilers are more prevalent.

According to the Estonian statistical database, in 2019, 15,760 million Tons of OS was burned for fuel generation out of which, the ash content generated was roughly about 40-60% [9], [10]. The reliance on OS in Estonia points more towards socio-economic reasons and/or political benefits rather than actual industrial requirements [6], [8].

OSA has shown proof to be an excellent strengthening additive that can be mixed with soil especially during road construction, such as with the pilot project at Taarikõnnu Tee. There are many uses of OSA and one such application is during the manufacture of cement where OSA is mixed with Portland Cement as a mixture. This increases its strength [7], [11]. However, less than 10% of the overall OSA produced has been utilised for construction purposes that also includes the road construction applications [10].

Furthermore, as per the EU’s strategy for Sustainable and Smart Mobility [12], [13], the emission reduction target for transportation is set for 100 European cities to become climate neutral by 2030. Infrastructure development has an impact as well. This is where the proposal to increase the usage of OSA from Estonian PPs instead of the traditional cement for road construction, comes into play. The aim of this study is as follows:

Aim of the thesis study: To calculate the carbon footprint of oil shale ash application in road construction via Life Cycle Assessment (LCA) approach.

2. THEORETICAL BACKGROUND

2.1 EU Targets for Transportation Mobility and Carbon Footprints

The EU has laid out several regulations pertaining to mobility, transportation and road construction. With regards to mobility within the EU member states, the union has charted out policies that ensure seamless, reliable and sustainable transportation [12], [13]. With transportation and mobility in general covering over 5% of the total GDP of the European continent, it has, arguably one of the largest carbon footprints; road construction follows closely, amounting to about one-quarter of the global CO_2 emissions [12]–[15].

Hence, in addition to ensuring that everyone within the European continent in the EU's member states are provided with easy and reliable movement both within and trans-boundary, policies governing a much greener and sustainable infrastructure development in the form of road constructions have been brought to the fore [12], [13], [15].

The EU's waste Framework Directive (or EU-WFD) 2008/98/EC requires all the EU states to comply with adopting practices to better reuse and recycle waste disposed illegally or legally to landfills for purposes of construction [16]. According to the Estonian legislation, OSA was classified as non-hazardous.

The Fifth Assessment of the IPCC, published in 2013-2014 brings into the picture, a *Carbon Budget* that defines how much CO_2 is to be emitted through anthropological activities. It was analysed in this assessment that global warming was the result of anthropological interventions that increased the overall atmospheric GHG quantities [17].

Studies have shown that the energy generation sector contributes to about 37.5% of the total CO_2 emissions. Naturally, the use of advanced technologies and the adoption of 'circular-economy' practices like the reuse of the generated waste, brings about a significant change in the overall carbon quantity and the carbon footprint [2], [7], [16]. In line with the IPCC's proposed targets, the EU has set its own range of decreasing emissions by 80-90% by 2050 and GHG emissions by about 20% and 40% by 2030 [4], [6].

2.2 The Energy Sector and Road Construction in EU and Estonia

From a broader perspective, the EU's major goals for boosting the energy sector is to reduce the imports of energy from neighbours and other countries while also ensuring that the MS are less dependent on this aspect. Simultaneously, yet another goal is to ensure the adoption of the development of sustainable and renewable energies as provided under the Renewable Energy Directive (2009/28/EC) [6], [18].

Although found in many countries like the USA, Estonia is the only country in the world where OS is pivotal to a country's economy. Falling in-line with the Renewable Energy Directive mentioned above, out of a set target of 25% gross renewable energy consumption, Estonia was the only country in the EU to cross the threshold of 17.5%, as per a Eurostat 2017 study. It accomplished its 2020 target [6].

Having said that however, the total reliance of the country on OS for heat and electricity generation is about 84%. OS is a calcareous fossil fuel that is also a major emitter of GHGs when burned.

Even though the total GHG emissions from the incineration of OS has significantly come down by about 47.5% since 1990, Estonia still holds the top spot when it comes to per capita rates of CO_2 emissions in the European continent [6].

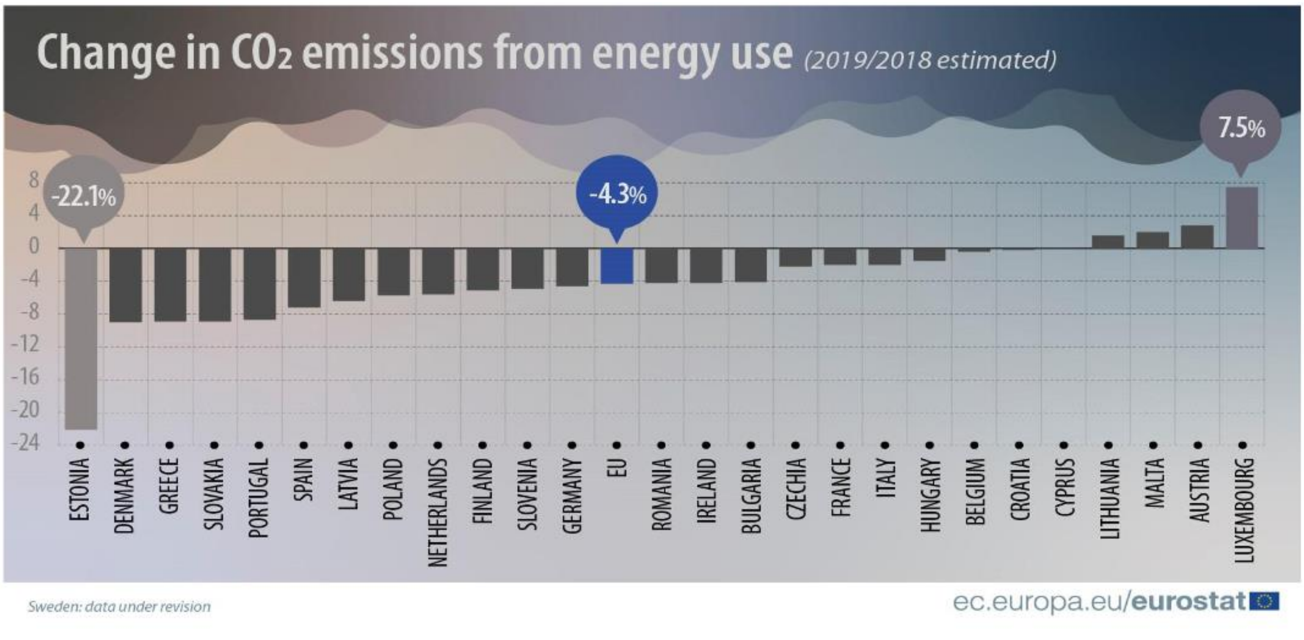

Figure 1:Change in CO2 Emissions in the EU MS as a result of energy use in 2019/2018 [19]

As seen in Figure 1, Estonia has recorded the highest dip in the CO_2 emissions primarily because of a decrease in the incineration of OS for energy generation and its switch to renewable energy sources [6].

According to Estonia's National Energy and Climate Plan 2030 (NCEP 2030) objectives, the percentage of overall renewable energy consumption must equal at least 42% by the year 2030. This includes a production quantity of half the total end-user consumption, equalling 16 TWh [20]. This dip in emissions is also related to the increase in prices of fossil fuel, by the EU (> 25€/t CO2) [19].

It has been shown through various studies [1], [21], [22] that the major sources of waste in the EU are from the construction and demolition sector and the quarrying and mining sector, with the former often having a much higher value relatively [21].

As can be seen in Berber et.al [23], the cement industry is the sector with the biggest carbon footprint and so steps to reduce this footprint has to be taken.

Connectivity has always been at the core of EU's sustainability goals and targets set for its member states to follow suit. However, various directives set by the EU previously has forced the union to come up with better and more efficient ways of setting laws and practices [16].

Decarbonisation in line with the Paris Agreement is possible by halving the overall quantity of CO_2 emitted by simply adopting the existing system of regulations and directives. However, cooperation and support from the member states are required as well in order to achieve this [24].

Although switching to biofuels to power up EU's cement and asphalt industries greatly contribute to lowering the harmful effects of climate change, in the event of a sudden shortage, a domino effect is created. Consequently, this will not let the EU reach its climate targets and carbon emission reductions pertaining to road construction, mobility and infrastructure development [24].

The Energy Conservation in Road Pavement Design and implementation (ECRPD) project initiated by the EU estimated and analysed the wear and tear of various layers of a road. It mandated procedures for the member states to follow so as to ensure better infrastructure, connectivity and better roads to be in line with the proposed climate targets [14].

It is, however, not plausible to completely describe the situation of road construction in the EU as a whole. In addition to making up the union, the member states also dictate how well the union's laws and protocols have been followed and adopted [16], [18], [21], [24].

In Estonia, a pilot project [25]–[27] has been successfully executed with satisfying results, the details of which would be discussed in detail under the methodology section of this thesis study. Here, a short stretch of a forest road amounting to about 1.2 Km was paved using OSA from Estonia PPs instead of using traditional cement for the road construction.

This is because of the abundantly available OSA that would otherwise be dumped to ash fields without any other purpose. Hence, Estonia smartly and efficiently minimised its carbon footprint by adopting CE norms [6]–[9], [23].

2.3 Composition of OS and Production of OSA in Estonian PPs

OS is present naturally in different forms each comprised of different mineral compositions. Ranging from calcareous to aluminosilicate, these minerals oxidise during incineration, thereby fundamentally getting their chemical compositions altered.

So, the OSA composition is not an exact reproduction of the original raw material and greatly depends on the type of combustion, retorting and temperatures set during the process [8], [28].

Kerogen is a major organic mineral found in OS that greatly varies with the geographical location and the conditions of the formation of the OS. When OS is incinerated, kerogen reacts and mainly releases GHGs [28]. The table below shows the mineral compounds of OS by its approximate percentage estimation.

Table 1: Estimated percentages of different minerals in OS. Reprinted from Pihu et.al [9]

Mineral Compounds in OS	**Approximate percentage estimated**
Calcite	44 %
Quartz	19.5 %
Dolomite	8.7 %
K-Feldspar	10.5 %
K-Mica	8.6 %
Total	**91.3 %**

CO_2 is the GHG that's commonly emitted as a result of the combustion. The major difference between PF and CFBC type boilers is in the temperature where the latter works on a much lower temperature because of which the calcium oxide formed is more reactive comparatively [9].

The chemical composition of OSA is vital during its application for construction, such as for the production of cement clinkers, as would be explained further ahead [9].

The table below shows different compounds and the respective content percentages as collected from *Field 1* and bottom ash:

Table 2: Mineral Compounds of OSA with their percentage compositions; Adapted from Pihu et.al [9]

Mineral Compound	**Percentage Composition (%)**		
	Bottom Ash	**ESP Field 1**	**Total Ash**
SiO_2	11.26	38.58	25.06
CaO	48.9	27.98	36.39
MgO	6.37	4.53	5.45
K_2O	1.15	4.47	2.76
Na_2O	0.1	0.24	0.2
SO_3	13.83	4.1	7.03
CO_2 (From CaO combustion)	38.07	21.78	28.33
CO_2 (From MgO combustion)	6.72	4.78	5.75
CO_2 (Total)	44.79	28.56	34.08

As seen, CaO is the most prominent mineral compound found in OSA. This is of significance because, when CaO is incinerated, it undergoes oxidation to give lime, which is impacts the environment negatively, when hydrated on land [9].

Estonian PPs such as the Balti PP and the Eesti PP have improved technologically. This is to accommodate for not only the changing times and increasing demands but to also reduce emissions and their carbon footprint. By this, the EU’s and the state’s set targets for environmental improvement are reached.

The CFBC is one such technique that these PPs have adopted where the OS is combusted at lower temperatures of about 700-800° C, compared to a significantly higher temperature of about 1300-1400° C as in Pulverising Firing (PF) boilers [7]–[9], [29].

Although the CFBC technique brought into view better energy extraction and efficiency techniques, combustion at such lowered temperatures also led to changes in the chemical compositions of the OSA that was collected in the filter [7]. This was also discussed in the topics above.

OSA is the end result of combustion of the mineral rich OS fuel where the primary goal of the incineration is to release the stored energy inside OS by the application of heat and energy [8].

Although present in abundance globally, this low-grade solid fuel is being utilised for commercial and economical purposes only in a few countries of which Estonia is one among the top. Similar to coal, OS is also a multi-mineral, solvent-soluble and insoluble organic, solid fuel that has trace contents of various other elements as well [8].

2.4 Application of OSA in Estonia: Cement Production for Construction Purposes

Approximately 7 million Tons of OSA ended up in ash fields in 2016 [9], [21], [23]. One of the most popular applications of OSA that has been in use in Estonia for quite some time now is in the manufacture of blended cement [7]–[9], [23], [29].

OSA has self-cementing properties, as evident from the study conducted by Usta et.al [7], where a detailed analysis of the binding strength, setting time, compressive strength and more such properties were discussed exhaustively.

The type of combustion used matters significantly as the temperature applied during the process alters the chemical composition accordingly. At lower temperatures during combustion, compounds such as CaO, MgO react to form compounds of belite, merwinite, etc by reaction with quartz, aluminosilicates and others.

All these define the quality of the end product formed by the use of OSA [9]. The study conducted by Usta et.al [7], clearly shows that the self-cementing ability of OSA with a coarser particle size and obtained from combustion at lower temperatures tend to give a lower grade output.

The curing property of the OSA is directly proportional to its extensive usage in road construction, strengthening and stabilising the ground [29]. It has been found that thermal power plants and cement manufacturing industries are the sites with arguably the biggest carbon footprints and so, it is only logical that alternating the usage of cement for the purposes of road construction with OSA that is available in abundance and simply disposed to ash fields would be the perfect method to close the CE loop [23].

2.5 Case Studies: Alternatives for Cement Used for Road Construction

2.5.1 Poland's Circular Economy Strategy

The concept of CE is technically where a material is kept within the loop through reuse or recycling. This was conspicuous in Poland. Poland is unique as it is one amongst the very few European countries to primarily depend on a single fuel source and in this case, it is coal. Hence, mining and quarrying are the most prevalent industrial activities, generating the highest waste quantity in the country [30].

The percentage of wastage in the mining sector is greater compared to the wastage in the construction sector- 42.3% Vs 9.5%. So, studies have proven that roughly 0.5 Tons of waste is being generated for every ton of coal mined from quarries [30].

Naturally, Poland has a very high potential to utilise the waste generated in a judicious manner. About 90% of PP waste in the form of coal ash is used for the purposes of manufacturing building materials for construction and road laying [30].

Reduction in carbon emissions was achieved through major investments in improving the technologies pertaining to the cement manufacturing sector. About 30% reduction was made possible through investments to technology [30].

Additionally, alternative fuels that replaced traditional fossil fuels were used to manufacture cement. Other methods included adopting sustainable incineration practices such as production of fuels by cement manufacturers themselves. Ultimately, about 1.7 MM tons of waste was saved [30].

2.5.2 Helsinki's usage of quarry fines for pavement construction

Although Helsinki lacks an abundant resource of OS, it still achieves CE targets by the re-usage of quarry fines (or quarry dust). Finland's low population density and its cold climate courtesy to its geographic location, often increases demand for aggregate usage. About 50 million tons of non-renewable aggregates are utilised for road construction [31]

Large quantities of quarry fines accumulated in the material made it easier to be disturbed by gravity and by the basic elements of the nature- Wind, Fire and Water [31].

Also, handling is further made difficult when the quarry fine is crushed to a very fine degree because of which it easily disperses in the air. This also brings about air pollution due to the dispersion of harmful Particulate Matter (PM) [31].

Hence, quarry fines in Finland can answer the country's demand for sustainable road engineering materials usage [31].

2.5.3 Comparison of the two case studies with Estonia

In many ways, Poland's case is very similar to the situation in Estonia. As discussed previously, Poland is a European country that is heavily dependent on a single source of solid fuel, namely coal [30].

Similarly, Estonia's power requirements are primarily met by the incineration of the abundantly available OS, a calcareous solid fossil fuel [8], [23], [29].

Both the countries boast of being majorly dependent on a single energy source and the waste generated is also being dumped to separately allocated ash fields [7], [9], [11], [30].

Hence, there is adequate potential for Estonia to make use of the abundantly disposed OSA, judiciously.

In the case of Finland, the stark similarity in the reusage of a secondary material (such as quarry fine in Finland and OSA in Estonia), shows the country's approach to fulfil EU's and CE's climate targets. Although cement is used for construction after blending with quarry fine, they have proven to be reliable with regards to their strength compared to fly ash usage [31].

Additionally, factors such as the lack of an abundant source of naturally available OS in Finland and excellent physical properties of quarry fines such as the swell, shrinkage and freeze-thaw rates, made it a natural choice for such a cold-climate country [31].

As discussed in Holmgrene et.al and Siksnelyte et.al [6], [18], Estonia's success rate in fulfilling EU's sustainability targets is very high which clearly shows the country's capability to undertake ambitious projects and fulfil them successfully.

3. METHODOLOGY

3.1 Description of the pilot case in Estonia: Taarikõnnu Tee

In line with the EU's environmental regulations, Estonia drafted the *Transport and Mobility Development Plan 2021-2035* [32], [33] to provide citizens with better and reliable transportation and mobility. The primary objective of the plan is to introduce a more sustainable infrastructure development that has a smaller carbon footprint.

The objective by 2035 is to meet EU's climate targets without compromising the quality of the public infrastructure. Under this aspect of the plan, road development remains an essential part to increase road safety and additionally, aid better connection of cities [32], [33].

Figure 2: A Google maps image of the stretch of Taarikõnnu Tee marked in orange

Taarikõnnu Tee in Western Estonia is a small section of an unpaved, forested road lined with a thin layer of hummus and other organics (Figures 2 and 3). The Taarikõnnu Nature Reserve is in the vicinity, however, provides no scope for environmental impact brought about by construction activities.

The presence of hummus and the soft soil were the main challenges faced during construction as it hindered with the overall estimation of the water required. Water was vital in blending the OSA with the soil [25], [27].

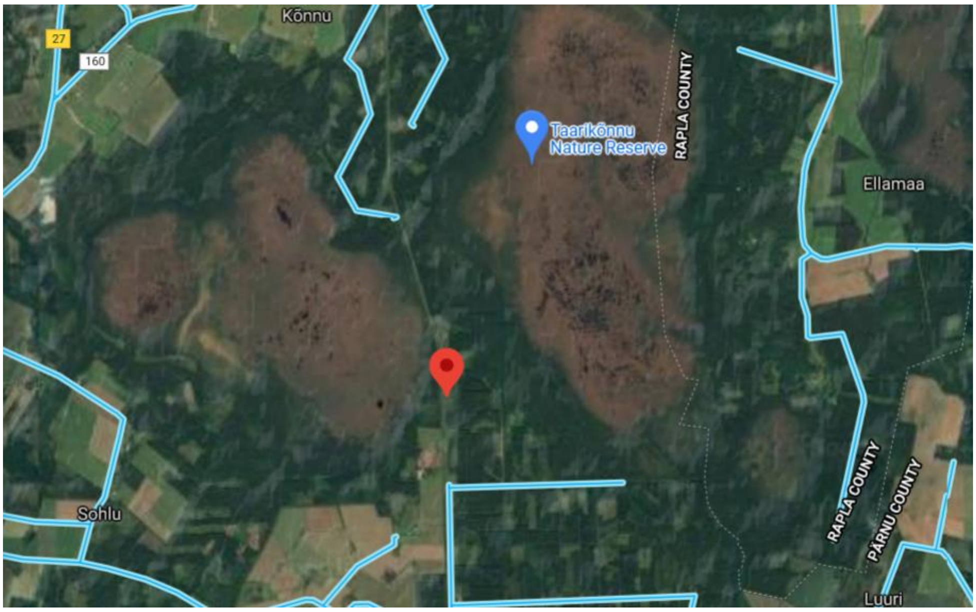

Figure 3: Location of the Taarikõnnu Tee project site as obtained from Google Maps.

The soil had to be prepared and profiled before road laying activities [27] . A stretch of about 1.2Km of the total available road of 3.14 Km was reconstructed using OSA mixed with the soil in two parts, instead of the traditionally used cement asphalt [25]–[27].

The letter of permit for the reconstruction that was issued by the Environmental Board of Estonia stated that this section of the road did not border or lie in close proximity to any protected or conserved area. This section of the road also did not lie in a 'building exclusion zone'. Reconstruction of the road, therefore, had no negative impact on the environment [26].

3.1.1 Overview of the road construction at Taarikõnnu Tee

The reconstruction started at an asphalt covered main road where it began. It stretched till the end of the road, Taarikõnnu Tee [26]. The following describes the steps involved in road laying and as executed at the pilot test site [25], [27]:

- **Two-Part Soil Preparation:**

  As seen in Sillamäe et.al's, Pärtel et.al's and Hiisjarv et.al's [25]–[27], the soil chosen for the pilot test project was an unpaved stretch of road in a forested area. Hence, presence of organic matter, plants, shrubs, dirt and hummus made it impossible to lay the road in the current state. Soil preparation was performed where stones, sticks, dirt, hummus, plants and any other unwanted litter and materials were removed in order to make the pathway more even for road laying purposes.

  Excess grass, weeds and stones were removed either using equipment or manually [25]. Work was carried out only in the section intended for the pilot case study, which had the following dimensions [26], [27]:

  <u>Length:</u> 1.2 Km or 1200 m

  <u>Width:</u> 4.5 m

  <u>Ditch:</u> 2 m

  The purpose of the ditch was to provide the area with enough leeway after clearing out about 2 m of rubble, dirt and organic matter [26]. Keeping in line with causing any environmental damage during the construction process, it was only necessary to remove a few tree stumps along the way to even out the pathway [26].

- **Soil Profiling:**

As seen in Galanti Et.al [34], soil profiling is the efficient removal of 0.5 cm to 5 cm of soil surface to rid it of unwanted materials. Often a destructive practice as it involves shifting and disturbing the soil layers, it is used judiciously nevertheless, as it ensures proper smoothening of the soil surface. A smooth and even surface is vital especially for road construction.

Although soil preparation involved the removal of stones, dirt and other materials, soil profiling removes larger stones and rocks greater than 20 cm. About 2-3 % of the soil was displaced during profiling.

This ensured that after the road was paved, rocks and pebbles did not interfere when the soil compactors were used to further even out the surface. This made sure that the strength and integrity of the soil was maintained. In short, soil profiling ensured that the entire stretch of the road was homogenous with regards to its strength and integrity [27].

- **Soil Stabilisation by mixing OSA in two parts:**

The soil that provides the foundation for any road has to be strong enough to withstand great amounts of stresses, forces and tension at all times in all weather conditions. Binders are added to the soil to further increase its integrity and load bearing capacity [35].

At Taarikõnnu tee, this was achieved by mixing the total OSA of 35 Kg/m^2 in two parts, with half of the quantity 17 Kg/m^2 of OSA mixed during the first binder laying process and the other half (17 Kg/m^2) mixed during the second round.

The mixing was done in two rounds to ensure complete blending of the OSA [27]. A total quantity of about 10 Kg/m^2 of water was used up for blending OSA with the soil [25], [27].

About 25 cm of the soil layer was mixed with OSA and stabilised during the first phase [27]. The primary problems faced during this process were because of the presence of organic matter like hummus in the soil.

Biodegradable and/or organic matter naturally have a certain amount of water in them. Hence, the difficulty in determining the quantity of water required initially was faced. This was soon rectified through trial-and-error method [25], [27].

The secondary predicament that was faced was in the transportation of the required quantity of water. This proved to be an issue because of the stabilisation of the soil that prevented heavy-duty trucks from traveling. Hence, regular trucks were used for the purpose [25].

It has been assumed that all the vehicles used during the road construction conformed to the Euro 6 emission standards [26], [36]–[38].

- **Sealing of soil using high-pressure rollers/soil compactors:**

After the process of mixing and blending of OSA into the soil, it had to be ensured that the next set of steps were done in the least possible time before the layer was fully set. The maximum allowed setting time of OSA was 4 hours from the time it was mixed to the soil. The sealing and smoothening of the road were done with the help of soil compactors [27].

The Proctor density is a set of pre-defined, laboratory proven soil compaction experiments popularly followed by civil engineers to determine the optimal moisture content for a soil by its weight.

These tests are broadly classified into two separate branches, the Standard Proctor Density (SPD) and the Modified Proctor Density (MPD). While the former is preferred for residential construction purposes, the latter is used for industrial construction purposes [39].

In this pilot case study, the SPD was used. As seen in Sillamäe et.al’s [27], a heavy-roller/soil compactor was used for the purposes of smoothening, levelling and stabilising the road layer.

While a minimum of at least 95% of SPD was to be ensured for significant soil integrity, at Taarikõnnu Tee, 100% of the total SPD was achieved, with a density value of $\rho = 1.65\ Mg/m^3$.

Additionally, heavy-duty trucks and vehicles were not allowed to travel over the freshly paved road to prevent cracking and disintegration of the road [27].

3.2 LCA Methodology: The Goal and Scope of the Study

The thesis is based on a Life Cycle Assessment (LCA) approach where all the essential steps initiating from the point of obtaining OSA from the Estonian PPs, to its end-usage as the major material for road construction are studied. LCA is a method of analysis of the life cycle of a product in the ecosystem, starting from its material extraction, manufacturing to its disposal or end-of-life stage.

This quantification of the bulk of the materials involved in the manufacture and ultimately in the disposal of the product has an impact often measured by the carbon footprint created. On a general basis, the carbon footprint calculation utilises the environmental impact of the raw material acquisition, material design/manufacture/processing, usage according to the system and finally, its disposal.

The goal and scope of the entire LCA study gives an insight of the OSA used in road construction. The goal of this study is to estimate the carbon footprint of OSA used for road construction via LCA methodology.

A pilot test project section at Taarikõnnu Tee has been chosen as the base for this assessment. This pilot section was chosen because OSA was used as a binder to construct this pilot section.

3.2.1 Functional Unit (FU)

189 t/Area of OSA for the entirety of 1.2 Km of the road constructed is considered as the functional unit for this assessment.

As discussed in the sections above, the total area of the unpaved section of road with a length of 1200 m and a width of 4.5 m equals to 5400 m^2. This gives us the total area for which the OSA is required for the construction of the road.

It is known from Sillamäe et.al’s and Pärtel et.al’s [25], [27] that 35 Kg/m^2 is the total quantity of OSA that is ultimately divided into two equal parts during the process of mixing with the soil to stabilise it. All calculations presented thereof in the inventory analysis table are based on this FU.

The first step where the assessment of OSA begins is in its collection from the PPs in Estonia. The OSA is transported through tubes to silos, where, after thorough filtration, is ultimately filled onto trucks of capacity 30 t. These trucks would reach the construction sites and unload the OSA for usage.

3.2.2 Defining the System Boundary

The system boundary is a well-defined outline chosen subjectively for the purposes of the study that gives an insight into what is considered for the assessment and what is excluded. All the elements defined outside the system boundary would not be considered for the assessment. System boundaries define the scope of the analysis.

In this assessment, all the processes associated with the generation of OSA in the PPs have been defined outside of the system boundary (Fig 3). The focal point of this assessment only pertains to the processes starting from the OSA collection from the filters and ends with the OSA being used for the construction section.

OSA dumped to landfills, air cleaned by the filters at the top of silos and pollutants to water at the construction site as a result of the activities involved thereof, are also defined outside of the system boundary.

Emissions to air and water usage are, however, considered inside the boundary as they are vital for carbon footprint calculations.

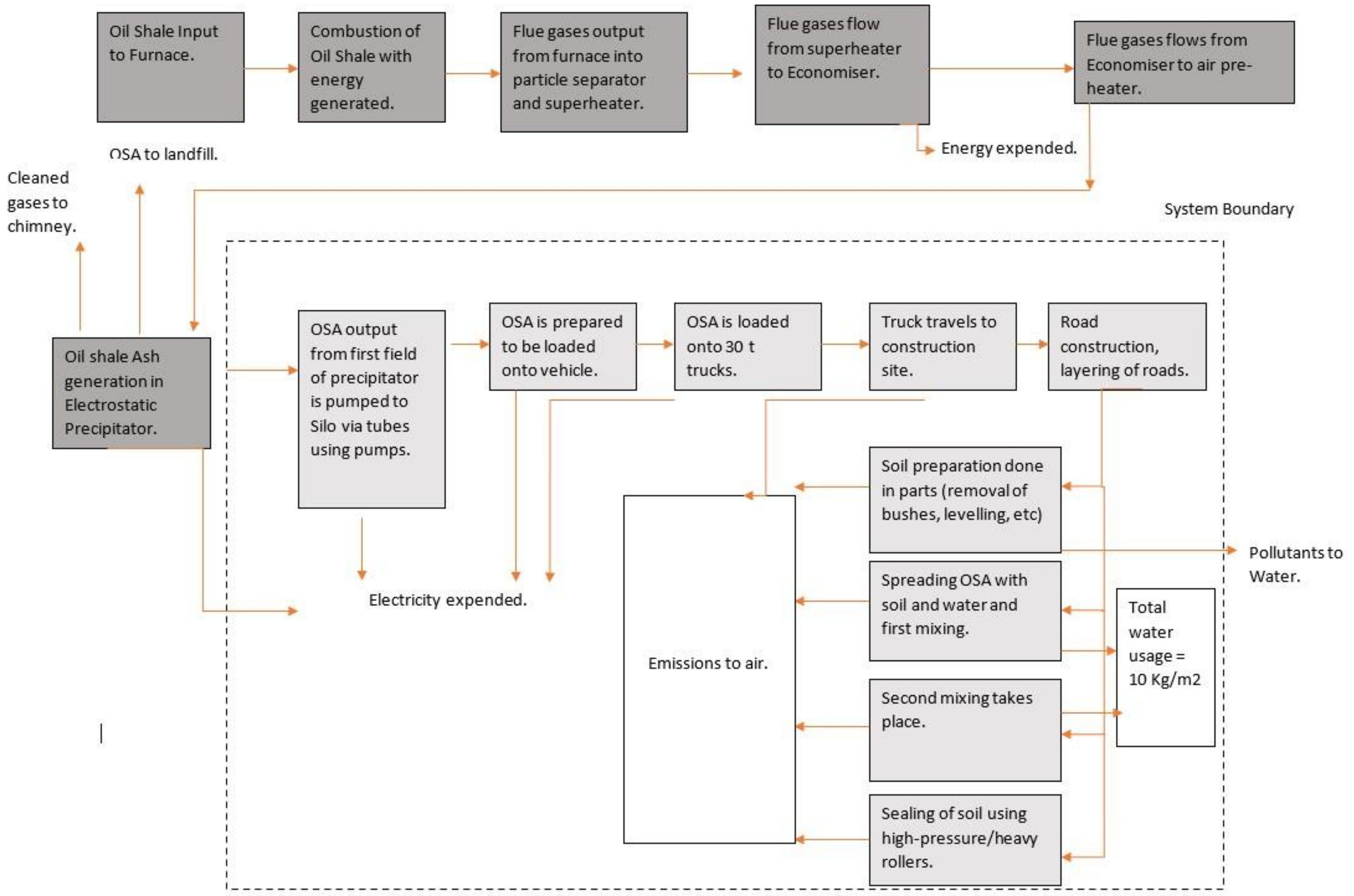

Figure 4: Flowchart with system boundary.

The electricity expended during the process of obtaining the OSA to the transportation of OSA to the construction sites by trucks are also considered as part of the system.

OSA from the filters is partly sent to the landfills. As seen however, this is outside of the system boundary and so, would not be considered for the final carbon footprint calculation. The cleaned gases are sent to the atmosphere after passing through a filter of a capacity of 26000 m^3/h.

This ensures that harmful PM 2.5 particles are filtered out before being released into the atmosphere. The filter has multiple fields or outlets used for multiple purposes. OSA output from these outlets (figure 3) is pumped to silo via tubes using pumps of capacity 160 KW.

The total quantity of ash that is pumped is 15 t/h or 360 t/day into silos of a total capacity of 3200 m^3. There are 8 such silos that are filled.

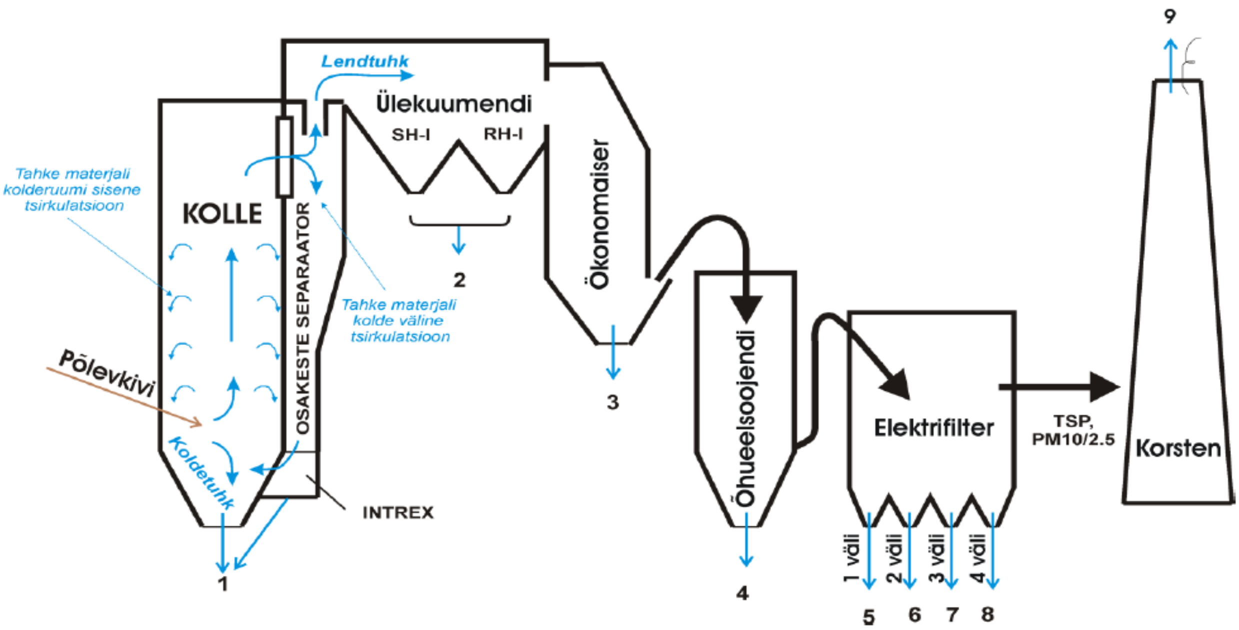

Figure 5: OSA collection in ESP that has multiple fields. The OSA is then transported to silos from where it is transported to trucks that reach designated construction sites [47]

The OSA obtained is unloaded to 30 t trucks using a pump of capacity 34 KW and the total quantity of ash transported to the vehicle at a single time is 40 m^3/h. These trucks travel to the construction site to unload the OSA that would eventually be used for road construction.

The distance between the PP and the construction section is also considered while compiling the inventory analysis table. The type and model of the trucks used for transportation is also of significance as different vehicles consume fuel and emit exhaust gases at different rates.

3.3 LCA Inventory Analysis

The table below shows the various inputs and outputs that are calculated and quantified as per the FU defined. The inputs and outputs adhere to the system boundary drawn in figure 4.

The values shown here under the “Value” column of the table are mostly real-world values obtained by enquiries made to experts in the field. Some of the values however, were obtained from databases such as Ecoinvent version 3.7.1.

The table below shows the complete list of inputs and outputs required for the process of OSA application in road construction at Taarikõnnu Tee. Some of the values have been rounded off to the nearest decimal for easier interpretation and calculations.

Table 3: Inventory Analysis

Inventory Assessment Table				
Name of process/Material	**Value/Quantity**	**Unit**	**Product per FU-189 t for 1.2 Km of ash**	**Units**
OSA from electrostatic filter				
Time taken to pump quantity of ash	15	t/h	**12.6**	h
Electricity Expended	160	KW	2016	KWh
OSA Pumped to Silo				
Electricity expended for filter in the silo	30	KW	378	KWh
OSA prepared to be loaded onto vehicle and Transportation				
Electricity Expended	34	KW	428.4	KWh
Total Truck Capacity	30	t		
Number of Trucks required			6	Units
Distance to pilot site by 1 truck	256	Km	512	Km
Distance to pilot site by 6 such trucks			3072	Km
Emissions of truck (Euro 6 emission norms; Calculations	0.11	Kg per t/Km	338	Kg per t/Km

done using CO_2 equivalent emissions).				
Machines used for Road Construction at Taarikõnnu Tee				
Bulk Density of 189 t of Ash	0.75	t/m^3	252	m^3
OSA Spreader- Assumed truck model- WIRTGEN Spreader SW16MC recycler	16	m^3	15.75	Trips
Distance travelled by OSA spreader in pilot section.	15.75	trips	18.9~19	Km
Emissions of CO_2 by OSA, assuming EURO 6 classification for truck; Info as obtained from OpenLCA	0.3	Kg per t/Km	68.4	Kg per t/Km
Soil Stabiliser workable width- Assumed truck model- WIRTGEN WS 250	2.5	m	1.8~2	Trips
Distance travelled by soil stabiliser in pilot section	1.8	Trips	2.16~2.2	Km
Emissions of CO_2 by soil stabiliser, assuming Euro 6 classification of truck	0.3	Kg per t/Km	0.65	Kg per t/Km
Additional materials for road construction				
Water	10	Kg/m2	54000	Kg

General Calculations:

1. The time taken to pump the quantity of the ash by electric pump of capacity 160 KW is considered as 15 t/h. This is divided by the FU to get the value of 12.6 hours. This forms the base for a few more calculations ahead.

2. The electricity expended by the pump is calculated for the 12.6 hours. The total capacity of the pump used here is 160 KW. In order to find the total energy used, this quantity is multiplied with the number of hours the pump is run. Here, 12.6 hours is sufficient for the pump to transport 189 tons of OSA out of the filter. Another pump is used to pump the OSA to the next stage of the processes.

3. A 30 KW capacity pump is used to transport the OSA out the filter to the silos. Totally, the energy consumption for this process where the pump is run for 12.6 hours is equal to 378 KWh.

4. Another pump is used to load the OSA to the vehicles. The capacity of this pump is 34 KW and the total electricity expended is calculated to be 428.4 KWh in the same manner that the other pumps were calculated.

Emission Calculations:

The emissions of the vehicles used in the entirety of this thesis was calculated as follows:

1. The distance (one-way) was found using Google Maps from Narva Elektrijaamad to Taarikõnnu tee to be 256 Km. This was calculated for the return journey as well and the total distance is 512 Km.

2. As per the Ecoinvent Database version 3.7.1, the CO_2 equivalent emission value is given as 0.11 Kg/ t*Km.

3. If the truck used for transporting the OSA from the PP to the construction site has a total quantity of 30 tons, then dividing the FU with this value gives us the total number of trucks required. The result is 6.3, which is rounded off to the nearest decimal to give us 6 trucks in total for the defined FU.

4. To calculate the total distance travelled by all the 6 trucks, 512 Km is multiplied by 6 to give us a total distance of 3072 Km.

5. The emissions from 6 trucks are calculated by simply multiplying 0.11 Kg per t/Km with the total distance travelled. This gives us 338 Kg t/Km. 0.11 Kg per t/Km was obtained from the Ecoinvent database version 3.7.1. The emission calculations are as shown below-

Emissions of 6 trucks = Total distance * 0.11 Kg t/Km Emissions = 3072 * 0.11 = 338 Kg t/Km

6. The emission calculations for the other vehicles have been estimated in a similar fashion. In the calculation of the emissions by the soil compactor however, the width of the machine and the width of the construction section have been considered instead of the quantity (mass and volume) units of the vehicle.

Assumptions:

1. The waste heat generated by the pumps during its operation has not been considered over here as sufficient information to calculate the same was unavailable.

2. The trucks used for the transportation of the OSA from the PP to the construction site and those vehicles used to construct the road conform to the Euro 6 emissions standards.

3. For the vehicles utilised for road construction, the information regarding the overall volume of these vehicles were obtained from the websites of the automotive companies themselves.

4. For this study, the OSA spreader and the soil compactors were of the model- WIRTGEN Spreader SW16MC recycler and WIRTGEN WS250 soil compactor respectively [36]–[38].

5. The trucks used for transportation only carries 30 tons during the first leg of its journey.

6. The closest approximations of the final values have been made wherever needed by rounding off to the nearest decimal places.

7. During the road construction, the OSA spreader does not refill during the many trips it makes along the length of the construction site (which is 1.2 Km). Hence, the assumption here is that the machine will always be full.

8. Finally, the soil compactor does not stop during the entirety of the process and 1.2 Km is considered as the total distance instead of 2.4 Km.

3.4 Calculation of the Carbon Footprint of OSA

The carbon footprint calculation in this assessment includes not just the transportation of OSA from the PP to the construction site, but also vital processes leading up to it. The capacity of the pumps used to transport OSA within the PP from one section to another creates its own footprint which is also taken into consideration.

The total energy (electricity) expended and hence the carbon footprint ultimately created throughout the processes are considered by utilising the total electricity expended, fuel used, distance between the PP and the test pilot site, the materials used for the construction and the impact of the vehicles such as the OSA spreader and the Soil Compactor used for road laying.

OpenLCA software was used to achieve this process and estimate the carbon footprint of OSA usage in road construction. The values were found out by loading the Ecoinvent 371 Cutoff database into the software and also by referring the Ecoinvent database version 3.7.1 Further references were made from the documents provided that recorded the processes involved in the construction of the road using OSA at Taarikõnnu tee.

The formula as mentioned in Milczarski Et.al [40] that is stated below provides the framework with which the calculation of the carbon footprint is based on.

Simultaneously, they are also in line with the International Standards of Life Cycle Assessment (ISO 14040 and ISO 14044) where the requirements and procedures for measuring partial carbon footprint are also specified in their document titled EVS-EN ISO 140667:2018.

Carbon Footprint (CF) = (Sum all raw materials consumed * Carbon emission factor from databases) + (Sum of all emissions GHG * The Global Warming Potential)

The transportation stage is slightly different, where the carbon footprint can be calculated only when the type and model of the trucks used for transportation and other machinery used for the purposes of constructing the road is known.

In this pilot test project, EURO 6 classification of trucks were used [36]–[38]. Estimating the carbon footprint for the transportation sector is as follows:

CF for Transportation = Total Quantity of OSA transported * Distance between PP and project site * Fuel consumed per unit distance

The outcome is expressed in units of Kg of CO_2 eq.

4. RESULTS

This chapter is dedicated for the results of the LCA study of the estimation of the carbon footprint of OSA application in road construction. The system boundary clearly describes the major processes considered in this study leading up to the road construction. The first process is where the OSA is obtained from the filter in the PP and transported to the silo. The processes that follow after, describe the transportation and ultimately, the construction of the road.

The environmental impacts of constructing a road using OSA as a layer blended with the soil have been discussed over here. Although the main focus of this study is on the climate change impact category under the midpoint impact assessment, two other essential midpoint categories such as Human Toxicity and Particulate Matter (PM) formation are discussed here.

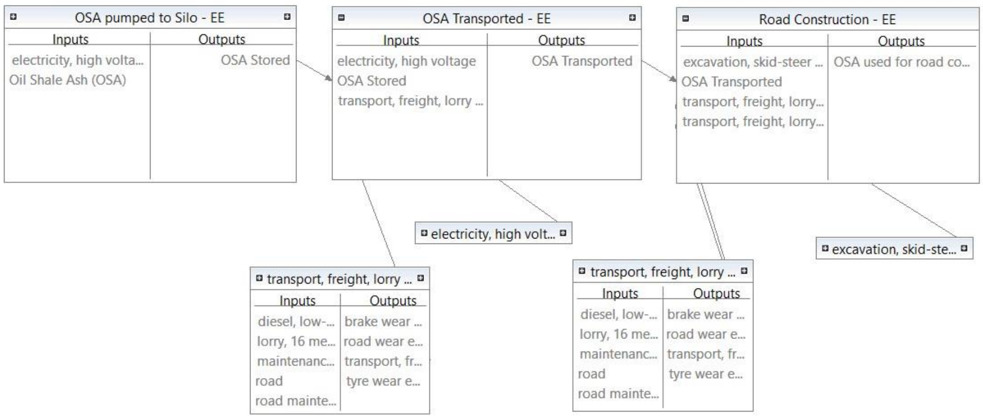

Figure 6: Model Graph of the Product System- Road Construction; Modelled using OpenLCA

4.1 Mid-Point Impact Assessment

The database used here are the ReCiPe Midpoint (H) version 1.1.3 and ReCiPe Endpoint (H, A). The ReCiPe database is unique because it combines the essential features, namely, the midpoint indicators as well as the endpoint indicators and allows to present the results at the damage level.

4.1.1 Carbon Footprint: Climate Change

The climate change GWP 100, which is an important environmental impact category for this study has an overall aggregated value of about 2110.4 Kg of CO_2 equivalent for 189 tons of OSA used for the road construction at Taarikõnnu Tee. Of these, electricity generation and transportation of OSA from the PP to the construction site has the highest contribution of about 634 Kg of CO_2 and 358.3 Kg of CO_2 equivalent respectively.

This is closely followed by soil excavation with a value of about 338.6 Kg of CO_2 equivalent. The values for the soil excavation and electricity generation are primarily because of the supply chain providers chosen, which is the production mix in Estonia and skid-steer loader for the soil excavation.

The production mix supply chain provider refers to the type of electricity that is produced through various sources such as biomass incineration, fossil fuel incineration, oil, gas and renewables. The value contribution of the vehicles used for the construction is about 70 Kg of CO_2 equivalent.

The supply chain providers for both the vehicles used, namely, the soil compactor and the OSA spreader corresponds to EURO 6 Freight and Lorry classifications. However, the relatively lower value is mainly because of only two primary vehicles considered for the road construction, namely the OSA spreader and the soil compactor.

The graph (figure 7) below shows the climate change GWP of the four most significant sectors:

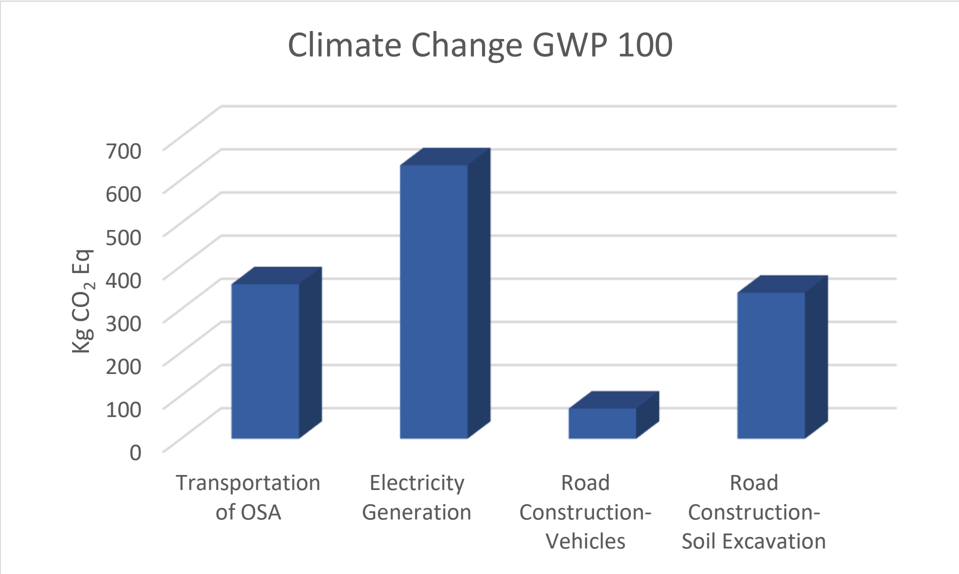

Figure 7: The CO_2 contribution of significant sectors, in Kg CO_2 Eq.

Overall, CO_2 and N_2O are the primary contributors for the climate change impact category. Under "Transportation of OSA", CO_2 equivalent in Kg emitted by the vehicles used can be seen clearly in Table 3. Electricity is an important aspect in these processes as the presence of pumps used to transport the OSA from one section to another within the PP creates a carbon footprint inadvertently. It was because of this reason that choosing an appropriate supply chain provider exclusive to Estonia in OpenLCA was critical.

4.1.2 Human Toxicity

Human Toxicity refers to the various emissions from any system to the environment that affects human health. It is expressed in 1,4 Dichlorobenzene equivalence (1,4 DCB Eq). Here, the major emissions as can be seen from Figure 8 point to the brake wear emissions from the various vehicles utilised.

Antimony (Sb) is a major source of metallic pollution that is prevalent in the form of aerosols and PM in the air especially in and around major highways [41].

Although different manufacturers prefer different metallic compositions based on the requirement for the manufacture of brake pads for vehicles, Sb and often Copper (Cu) are commonly known tracers. Sb is a highly useful, yet toxic element in trace quantities. The constant braking and usage of the component leads to abrasion because of which Sb is emitted to the air [41].

Over here, the quantity of Sb is the highest under brake wear emissions for transportation with a total quantity of about 0.007 Kg and an impact factor of about 6760 Kg 1,4 DCB Eq. For vehicles used for construction, the total quantity of Sb emissions is 0.003 Kg 1,4 DCB Eq. This is closely followed by Lead (Pb), which is yet another naturally toxic element. Electricity generation is yet another sector with a high human toxicity impact factor. In this study, human toxicity has a total impact factor of about 242.6 Kg 1,4 DCB Eq.

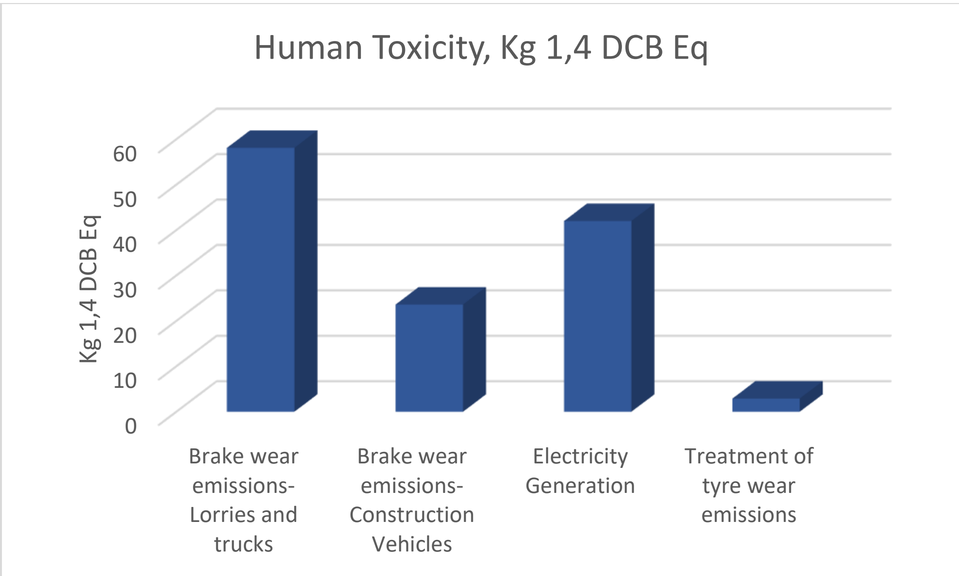

Figure 8: The Human Toxicity contribution in significant sectors.

4.1.3 Particulate Matter Formation

The emission of oxides of NOx, NH_3, SO_2 or essential particulate matter such as PM 2.5 to the atmosphere constitutes the Particulate Matter impact category. The values are expressed in PM10 Eq impact category units and here, it has a total of 4.15 Kg PM10 Eq.

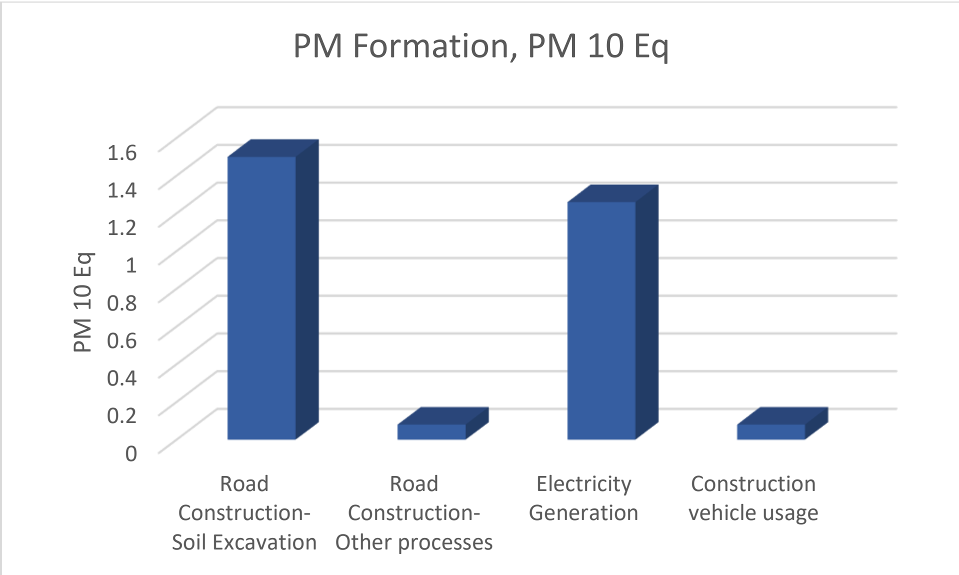

Figure 9: Particulate Matter formation represented by the most significant sectors.

The major contributors here are from the soil excavation processes. The supply provider was chosen in the OpenLCA software for an overall quantity of 819 m^3 of soil excavated during the construction of the road.

As can be seen from the graph above, the PM formation factor for other processes involved in road construction is not very high comparatively because only a few significant machineries were considered for the purposes of this assessment, namely the OSA spreader, the soil compactor and the soil excavator.

Electricity generation has the tendency to emit oxides of Sulphur, Nitrogen and Particulate matter (PM 2.5-PM 10) based on the supply chain provider chosen here and so, it has a high value that closely follows the soil excavation process.

4.1.4 Other Mid-point impact indicators

Other midpoint indicators that were a little less vital for this study although had significant values were Fossil Depletion, Terrestrial ecotoxicity and Terrestrial Acidification. Under Fossil Depletion, the major impact contributor was crude oil.

Although the electricity produced in this study was through the incineration of the OS, other parameters involved in this process such as transportation for example requires other forms of fossil fuel. The impacts were also because of the supply chain provider chosen, which was the production mix exclusive to Estonia.

These fuels are obtained by combusting crude oil obtained from the ground. Trucks, lorries and construction vehicles require fossil fuels like petrol/diesel to run and hence, this was considered another significant impact category. It had a total value of 573.5 Kg of Oil eq.

Terrestrial ecotoxicity refers to the transformation of chemicals in the environment thereby affecting the lives of terrestrial species and aquatic ecosystems. It is measured in units of Kg 1,4 DCG Eq and here, it has a total value of about 0.35 Kg 1,4 DCG Eq.

The major contributor is from the disposal of worn brake pads from trucks used for transportation and here, has a value of about 0.14 Kg 1,4 of DCB Eq. Yet another contributor that follows is electricity production with a value of about 0.08 Kg 1,4 of DCB Eq.

Terrestrial Acidification refers to the impacts caused to the land/soil properties due to the transformation of chemicals in the ecosystem. It is measured in units of Kg SO_2 Eq and here, has a total value of about 10.14 Kg of SO_2, with the major contributors being electricity generation and site preparation through soil excavation.

4.2 End-point Impact Assessment

The results in this section evaluate three specific end-point categories, namely Ecosystem Quality, Human Health- and Resources.

The ReCiPe database in OpenLCA evaluates these three aspects with three different units, namely- Species lost for Ecosystem Quality, Disability Adjusted Life years (DALY) for Human Health and Economic Loss for Resources.

Hence, in order to unify and standardise these values under different units into one common unit for the purposes of comparison, normalisation is done. Hence, all the values expressed here are as points and in no particular units.

Tree-map charts are useful to get an idea of the parameters with the biggest impacts/values. They are represented as rectangles and the bigger a rectangle is, higher is the impact, here. The graph below (Figure 10) shows a tree-map of the major end-point indicators.

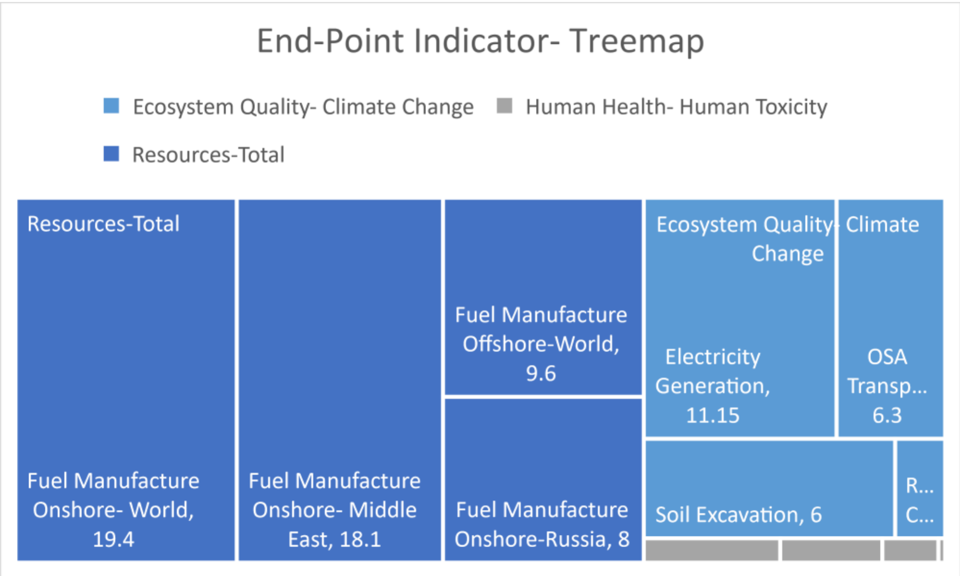

Figure 10: Tree-map of the major End-point indicators

Clearly, the resources used is the worst affected with the highest impacts. The major contributors under this category are from the fuels used to power vehicles used for transportation of OSA from the PP to the construction site, from the electricity generation for the pumps used in the PP and the construction vehicles.

The category that closely follows is the Ecosystem Quality category. This is primarily because of the generated electricity that powers the pumps used in the OS incineration plants. The fundamental process of electricity generation as per the supply chain provider chosen here also tends to generate a significant quantity of CO_2 emissions.

The usage of vehicles for hauling the OSA from the PP and the vehicles used for constructing the road are other main contributors in this category. Manufacture of the fuel required also goes into this category and so, the impacts are significantly greater from the perspective of carbon footprints created.

It can be observed that the human health is not very affected. Although all the results exhibited so far are majorly based on a few assumptions and approximations, human health category in this study was observed to primarily be due to wear and disposal of brake components in the vehicles.

These are not large in number from a broader perspective and so, the end-point characteristic represents the same. The tables below show the values, in points, for each of these impact categories:

Table 4: Ecosystem Quality for Climate Change (units in points)

Ecosystem Quality (Points)			
OSA Transported	**Electricity Generation**	**Road Construction**	**Soil Excavation**
6.3	11.2	1.2	6

Table 5: Human Health for Human Toxicity (Units in points)

Human Health (Points)			
Brake Components Disposal-Transport	**Brake Components Disposal-Road construction**	**Electricity Generation**	**Fuel Manufacture**
0.8	0.3	0.6	0.04

Table 6: The resources impact category; The total resources considered here (units in points)

Resources (Points)			
Fuel Manufacture Onshore-World	**Fuel Manufacture Onshore-Middle East**	**Fuel Manufacture Offshore-World**	**Fuel Manufacture Onshore-Russia**
19.4	18.1	9.6	8

5. DISCUSSIONS AND CONCLUSIONS

The results shown and explained here are in good agreement with the FU defined. Being a relatively new process, there was a dearth of sufficient information and values in the databases used thereof. However, by considering the closest and the best approximations, a general idea of the impacts of OSA usage for road construction and the estimation of the carbon footprint of the processes involved were achieved.

Further discussions interpreting the results and the reason why adopting the usage of OSA for purposes other than its disposal to ash fields are shown in the forthcoming sections.

The existing literature pertaining to OSA usage for road construction are very few in number and majorly describe outdated OS incineration technologies used in PPs. For example, the PF incineration technology that has been discontinued in Estonian PPs and replaced by CFBC incineration type.

The latter provides an eco-friendlier OS combustion [7]–[9], [11], [29]. This is a noteworthy point because the type of combustion and the processes involved thereof greatly affects the emissions and energy consumption.

Additionally, the type of combustion technology used also affects the quality of OSA obtained after combustion, which inadvertently introduces changes to resources and energy demands upstream in the process.

The ambiguities that exist and assumptions made to the system boundary as shown in figure 4, compared to other similar studies bring about a few more challenges pertaining to the accuracy of the results estimated.

5.1 Interpreting the Product System

As seen in figure 6, the model graph of the product system created using the OpenLCA software lists out the three vital processes involved in this study, namely- OSA pumped to silo, OSA Transported and Road Construction. The three processes have been linked by using the output flow of one process as the input flow of the next. The output flow of the process "OSA pumped to silo" is "OSA stored". This is considered as the input for the next process, "OSA Transported".

The output flow of this process was the total quantity of 189 tons of OSA transported using trucks to the construction site. The final flow of the last process defines the road construction.

Due to the unavailability of sufficient data for OSA produced, used or for OS extraction in the databases in OpenLCA, there was a need for a new flow called "Oil Shale Ash (OSA)" to be created. As OSA is essentially the waste generated as a result of combustion of OS, the flow property was chosen as a "waste flow". Contrary to common practice, this flow was chosen in the input stream as it formed the essence of this study.

5.2 An Alternative Functional Unit (FU)

The FU considered for the entirety of this study is 189 tons of OSA for a distance of 1.2 Km of road. This was calculated using a known data value of 35 Kg/m^2 of OSA required for the construction made at Taarikõnnu Tee. A more fundamental, alternative FU that this study considers a possibility is 1 ton of ash for 1 Km of road constructed.

However, this could introduce a need for approximations as, the actual FU defined in this study and used for estimations, is the theoretical estimation of real-world values used for the construction of 1.2 Km of road at Taarikõnnu Tee. The reason for the consideration of the theoretical estimation rather than the data used during practical application is the lack of sufficient data from the databases used.

It has to be mentioned, however, that the database used for the estimation of the carbon footprint of this process was the current version of the "Ecoinvent-371 cut off unit (20210104)".

5.3 Interpreting Major End-point Impact Categories

As seen in figure 10, the category with the highest impact is "Resources". In order to interpret this, the subsequent biggest category has to be noted, namely, the "Ecosystem Quality". The distance between the PP and the construction site in this study is very large. Based on the assumptions made to the manufacturing model and number of vehicles used for the transportation of OSA and for the construction of the road, the need for a large amount of fuel is justified.

Additionally, the manufacture of automotive fuels is a resource-intensive process and so, the values shown in the tree-map in figure 10 provides an approximation of the supply chain provider chosen for the values used for the input process flows.

In Yuansheng and Mengshu's [42] case study of the CFBC type of incineration for coal in China, an analysis for the environmental effectiveness of this system of fuel combustion was established. The authors claimed that the combustion characteristics of coal using CFBC significantly reduced CO_2, SO_2 oxides of Nitrogen and PM as compared to other forms of combustion techniques.

Both the internal and the external environmental benefits were calculated by comparison with the pulverised coal furnace techniques. The cost-benefit analysis was also analysed and the result came out in favour of the CFBC incineration technique.

The cost-benefit analysis was performed by creating a Single Hidden Layer Feedforward Neural Network, a type of machine learning algorithm to optimise all the parameters in the inputs and the outputs [42]. Hence, it was shown that in addition to being environmentally sustainable, the CFBC technique also reduced the cost.

Although developing newer and better combustion technologies in PPs are the way forward, they are often expensive and take a longer time to implement fully. In such cases, the next best alternative is to reduce the carbon footprint created in the transportation and the logistics sector.

There are many studies which provide ample proof of scope for the use of electric heavy-duty vehicles in the Transportation and Logistics sector. Making this sector more sustainable is one efficient way to significantly reduce the carbon footprint. As can be seen in Croci.E et.al [43] the analysis conducted on heavy-duty fleet vehicles has been based on real-world data.

Here, the author has provided sufficient evidence to support the claim made that there is a significant reduction in the impact categories pertaining to Photochemical Smog formation, Climate Change and Acidification. The LCA modelling used in this study was based on the CML Baseline database that was loaded onto SimaPro 8.4 LCA software [43].

The adoption of a fully-functional diesel vehicle fleet specialising in logistics and transportation increases the PM formation by about 13% as per the LCA conducted. This is mainly because of the type of electricity production mix supply chain provider that utilises fossil fuels for electricity generation. The author provides ample proof to support the claim that adoption of EVs offsets the increased PM formation when alternative sources of energy are utilised [43].

This is in line with Dorota et.al’s [44] claims, where the authors had proved that switching to more renewable energy sources was better. Their LCA, based on a case study of two countries, namely Poland and the Czech Republic, has shown evidence that the former’s impact factors were significantly higher than the latter’s.

The reason pointed out was Poland’s reliance on a specific type of electricity production mix that mainly relied on fossil fuels. Czech Republic showed potential for an increased reliance on renewable nuclear energy sources and hence, had a much lower overall impact comparatively [44].

The electricity used for recharging the batteries were the main basis of this study that was conducted using SimaPro 8.5 that was loaded with the Ecoinvent Version 3.0 database. The LCIA methodology used was the ReCiPe Midpoint and a 95% confidence interval for the uncertainty estimation was considered [44].

In yet another study, Viktorovich et.al [45], the authors have described in detail the ease of switching to alternate fuels sources for vehicles instead of major investments and changes brought about in the electronic vehicle manufacturing sector.

Here, the study was not only based on today’s scenario but was also a forecast of the future by claiming that there will be a reduction in the reliance of gasoline by about 11.4% by the year 2040. The share of alternative fuel sources was on an increase from 9.4% to 24% as per the study.

Although the study was based on Russia’s road transportation status, it was shown that the import of vehicles from EU and Japan had no significant effect on the dynamics of the study [45].

Thus, it can be said that there are avenues through which the logistics and transportation sector can be made more efficient and sustainable by either the adoption of an all-electric vehicle fleet or alternative fuel sources for the internal combustion engine vehicles that are already in use.

As seen in Schulte and Ny [46], Burchart-Korol et.al [44] and Croci et.al [43], The GHG emissions are far less significant when the energy sources and the production mix for electricity generation are renewable energies rather than fossil-fuel based energy sources.

Although the impacts caused during the manufacture of electric vehicles are higher than those of internal combustion engine vehicles, they are offset in about 2-5 years of continued vehicle usage.

5.4 Limitations of this Study

The following are the limitations posed by this study:

- Information related to OS was unavailable in any of the databases used in this study (Ecoinvent and the Ecoinvent 317 cutoff used in OpenLCA). So, for the purposes of progressing with the analysis, certain essential product flows in OpenLCA had to be created manually.
- The system boundary created here excludes the major OS combustion processes. This LCA does not adopt the cradle to grave approach and so, all the processes linked with the extraction, processing and combustion of OS for electricity production are disregarded for this study. Consequently, disposal of OSA to ash fields have also not been considered.
- This is of significance because the combustion of OS has a comparatively higher carbon footprint when all the sub-processes leading up to power generation are also considered.
- PM2.5 formation emitted from the furnaces as a result of OS incineration lies outside the system boundary.
- Pipelines made of a special compound of hard plastic are used as a link between the filter and the silos during the pumping of OSA. Sufficient information for the constituents making up this pipeline was unavailable and so, it has been excluded from the system.
- There wasn’t sufficient information available to estimate the wasted heat from the pumps used for the purposes of pumping the OSA from one stage to another. Hence, the impact of wasted heat was not included directly as an output flow in any of the processes created.

- The pollutants emitted to water during road construction has not been considered either. This has not been added to the flows during modelling in OpenLCA.
- Information pertaining to the fuel consumed by the vehicles used on-site during road construction was unavailable. So, it was impossible to calculate the calorific value of the fuel.

5.5 Conclusion

The EU's smart and sustainable transportation mobility aims to modernise, provide reliable and eco-friendlier transportation and infrastructure in EU by 2030. A rapid increase in global concerns over rising CO_2 levels in the atmosphere due to anthropological interventions majorly, has shown an urgent need to curb emissions and bring down the levels.

This was also made clear by the targets set by the IPCC and the Paris Agreements which have coaxed countries to curb their emissions and mitigate environmentally harmful practises. The latter has defined targets to reduce overall global temperature by about 1.5 ° C by 2030.

Estonia's high reliance on OS to meet its energy demands meant that the waste OSA produced was generally high. However, studies have shown that only a very small percentage of this was utilised for other purposes, while a major percentage often ended up in ash fields. This caused other environmental impacts such as terrestrial ecotoxicity, terrestrial acidification, marine ecotoxicity, etc.

Reference studies provided in this study has proved that OSA exhibited cementitious hardening properties when blended with soil and water. Therefore, OSA showed potential to be used for construction purposes in the place of traditional cement instead of disposal to ash fields.

This proved to be one of the best uses of waste OSA as the construction sector contributes close to 30% of the overall CO_2 emitted, as was proved by reports and studies.

Additionally, the cement industry has shown to be a very environmentally unfriendly industry with a large carbon footprint. So, the gradual adoption of OSA usage in the place of cement for construction wherever possible would bring about a noticeable change in reducing the carbon footprint.

This entire study has been based on a real-life case study, where a stretch of 1.2 Km of a forested area called Taarikõnnu Tee in the western part of Estonia was constructed using approximately 189 tons of OSA.

The LCA done for a functional unit of 189 tons of OSA for 1.2 Km of road has shown that the electricity generation and the transportation sector have the largest carbon footprint with a total value of 634 Kg CO_2 Eq and 358.3 Kg of CO_2 Eq respectively. Soil excavation had a total carbon footprint of 338.6 Kg of CO_2. Overall, the carbon footprint was calculated to be 2110.4 Kg of CO_2 Eq.

Having said that however, several assumptions were made in the course of this study to ease calculations and analysis. The relative newness of the topic and the lack of sufficient data in the databases thereof has introduced a handful of limitations to this study.

Recommendations to make the transportation and logistics sector eco-friendlier with a much lesser carbon footprint have been provided with sufficient backing studies. The adoption of an all-electric fleet of vehicles does not seem egalitarian as the technology to achieve it already exists.

Furthermore, the adoption of alternative fuel sources is yet another method to reduce the carbon footprint. All these were proved to be better alternatives to introducing constant technological changes to combustion techniques in PPs.

Because of the assumptions made and consequently the limitations that were posed, this study has only provided a partial picture of the scenario of the carbon footprint of OSA usage in road construction. The impact categories lean heavily towards the category of transportation of OSA from the PP to the construction site.

However, the essence of the OSA formation which is the combustion of OS was excluded from the system. If it were included, then the outcome would lean towards these processes more than the transportation sector, which would seem lesser, comparatively.

The traditional method of constructing a road using cement already brings with it a significantly higher carbon footprint, which is more difficult to reduce despite the advancements in the transportation and logistics sector. Therefore, it can be said that the usage of OSA for the purposes of road construction has a very good potential to have a much lesser carbon footprint comparatively.

In the end, however, further study and investigations are required in the usage of OSA for road construction, where all the parameters missed out in this study would be considered for the analysis.

SUMMARY

There is a need to adopt eco-friendlier and more sustainable construction practises. This is also in line with the targets and objectives set by the CE concept of waste reuse. The construction and transportation sectors are already one of the biggest carbon emitters in EU.

So, a shift in focus towards reusing the waste generated especially in the industrial and energy generation sector is essential. In particular, in this study, the focus has been in the OSA application in road construction.

An LCA approach was used in this study to analyse the impacts created because of the application of OSA in the economically better sectors. It has been estimated and concluded that despite the high footprint created by the electricity generation and the transportation sectors, OSA application for construction still showed a great potential for carbon footprint reduction.

The system boundary created in this study started only from the point OSA was transported to the silos using pumps. The LCA did not adopt a cradle to gate or cradle to grave approach. The focus was kept specifically in the application of OSA for road construction.

The literary overview provided an exhaustive background of this study to the reader. Real-world case studies in EU where similar projects were successfully executed were also discussed. Sufficient references were made to provide a solid backing to the overview presented.

The methodology section described the construction at Taarikõnnu Tee using OSA blended with soil and an overall quantity of 10 Kg/m^2 of water.

The various steps involved in the construction site had been mentioned. The FU of 189 tons of OSA for 1.2 Km of road was defined and the system boundary was drawn.

The inventory assessment tabulation provided the essentials without which the construction wouldn't have been made possible. A brief description of how the carbon footprint was calculated using the OpenLCA using a generic formula was also explained.

All the relevant data obtained to fulfil the inventory assessment tabulation were obtained from experts in the field and they reflect real-world data and scenarios. This greatly increased the accuracy of the study despite the assumptions made and the limitations posed thereof.

The carbon footprint was ultimately estimated using the OpenLCA software that was loaded with the "Ecoinvent 371 cut-off" database and the ReCiPe version 1.13 Midpoint (H) and the ReCiPe Endpoint (H, A) LCIA methods were used for the midpoint and the end-point calculations. Ecoinvent version 3.7.1 was also made use of wherever possible and required.

In the midpoint level, the major impact categories were the climate change: carbon footprint with a total value of about 2110.4 Kg of CO_2 Eq, Human Toxicity with a total value of about 242.6 Kg 1,4 DCB Eq and PM formation with a total value of about 4.15 PM 10 Eq.

The major sources of impacts in these categories were from the transportation and the energy generation sector. This was chalked up to the assumptions made, the selective system boundary chosen and the supply chain provider for the electricity used. In the PM formation however, road construction showed to be the highest contributor.

The end-point estimations were made as well and the normalised values were mentioned in points. Three major categories, namely, Ecosystem Quality, Human Health and Resources were considered. Out of these, the Resources showed the greatest impact mainly because of the transportation sector.

This was reasoned out by pointing to the distance between the PP and the construction site and the number of trucks needed to transport 189 tons of OSA.

This impact was closely followed by the Ecosystem Quality used and it was justified by the fact that vehicles needed fuel for running and manufacture of fuels have a huge environmental impact.

The product system was discussed in detail and the possibility of an alternative FU of 1 ton of OSA for 1 Km was also discussed. Recommendations to make the transportation and logistics sectors more reliable and sustainable were provided after discussing the end-point impact categories in detail.

The limitations of the scope of this study have showed that the study provides a somewhat partial viewpoint towards OSA application in road construction. The assumptions and the lack of sufficient information from the databases only added to this point. It was therefore, concluded that further investigations were required with all the missed-out parameters included into the system.

REFERENCES

[1] D. Choi, Z. Gao, and W. Jiang, “Attention to Global Warming,” *The Society of Financial Studies*, pp. 8–10, 2020, doi: 10.1093/rfs/hhz086.

[2] L. Al-Ghussain, “Global warming: review on driving forces and mitigation,” *Environmental Progress and Sustainable Energy*, vol. 38, no. 1. John Wiley and Sons Inc., pp. 1–7, Jan. 01, 2019, doi: 10.1002/ep.13041.

[3] L. Clarke and M. Sahin-Dikmen, “Unions and the green transition in construction in Europe: Contrasting visions,” *European Journal of Industrial Relations*, vol. 26(4), no. 4, pp. 1–3, 2020, doi: 10.1177/0959680120951705.

[4] V. Duscha, A. Denishchenkova, and J. Wachsmuth, “Achievability of the Paris Agreement targets in the EU: demand-side reduction potentials in a carbon budget perspective,” *Climate Policy*, vol. 19, no. 2, pp. 161–174, Feb. 2019, doi: 10.1080/14693062.2018.1471385.

[5] Maxwell Boykoff and Olivia Pearman, “Now or Never: How Media Coverage of the IPCC Special Report on 1.5°C Shaped Climate-Action Deadlines | Elsevier Enhanced Reader,” *One Earth Commentary- Gold Standard for Global Goals*, pp. 1–2, 2019, Accessed: Jun. 16, 2021. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S259033221930140X?token=276249FDF283F49BA01C50F6725D502AFBC674E9FBE944E51F283904D311419E2DE5ABB137C9BB90C3FB14F2CDCD2029&originRegion=eu-west-1&originCreation=20210616114154.

[6] S. Holmgren, M. Pever, and K. Fischer, “Constructing low-carbon futures? Competing storylines in the Estonian energy sector’s translation of EU energy goals,” *Energy Policy- Elsevier*, vol. 135, pp. 1–3, Dec. 2019, doi: 10.1016/j.enpol.2019.111063.

[7] M. C. Usta *et al.*, “Evaluation of new applications of oil shale ashes in building materials,” *MDPI-Minerals*, vol. 10, no. 9, pp. 1–3, Sep. 2020, doi: 10.3390/min10090765.

[8] Vahur Oja and Eric M. Suuberg, “Oil Shale Processing, Chemistry and Technology,” in *Encyclopedia of Sustainability Science and Technology*, Springer New York, 2012, pp. 4–10.

[9] T. Pihu, A. Konist, E. Puura, M. Liira, and K. Kirsimäe, “Properties and environmental impact of oil shale ash landfills,” *Oil Shale*, vol. 36, no. 2, pp. 1–5, Jun. 2019, doi: 10.3176/oil.2019.2.01.

[10] T. Pihu *et al.*, “Oil shale CFBC ash cementation properties in ash fields,” *Fuel*, vol. 93, pp. 1–3, Mar. 2012, doi: 10.1016/J.FUEL.2011.08.050.

[11] P. Paaver, P. Paiste, M. Liira, and K. Kirsimäe, “Mechanical activation of the ca-rich circulating fluidized bed combustion fly ash: Development of an alternative binder system,” *MDPI- Minerals*, vol. 11, no. 1, pp. 1–3, Jan. 2021, doi: 10.3390/min11010003.

[12] European Commission, “COMMITTEE AND THE COMMITTEE OF THE REGIONS Sustainable and Smart Mobility Strategy-putting European transport on track for the future {SWD(2020) 331 final},” 2020.

[13] European Commission, “COMMITTEE AND THE COMMITTEE OF THE REGIONS Sustainable and Smart Mobility Strategy-putting European transport on track for the future {SWD(2020) 331 final},” 2020.

[14] G. Trunzo, L. Moretti, and A. D'Andrea, "Life cycle analysis of road construction and use," *Sustainability (Switzerland)*, vol. 11, no. 2, pp. 1–2, Jan. 2019, doi: 10.3390/su11020377.
[15] A. Stefaniec, K. Hosseini, S. Assani, S. M. Hosseini, and Y. Li, "Social sustainability of regional transportation: An assessment framework with application to EU road transport," *Socio-Economic Planning Sciences*, pp. 2–3, May 2021, doi: 10.1016/j.seps.2021.101088.
[16] D. Noll, D. Wiedenhofer, A. Miatto, and S. J. Singh, "The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: An island's dilemma," *Resources, Conservation and Recycling*, vol. 150, pp. 1–8, Nov. 2019, doi: 10.1016/j.resconrec.2019.104405.
[17] B. Lahn, "Changing climate change: The carbon budget and the modifying-work of the IPCC," *Social Studies of Science*, vol. 51, no. 1, pp. 1–8, Feb. 2021, doi: 10.1177/0306312720941933.
[18] I. Siksnelyte, E. K. Zavadskas, R. Bausys, and D. Streimikiene, "Implementation of EU energy policy priorities in the Baltic Sea Region countries: Sustainability assessment based on neutrosophic MULTIMOORA method," *Energy Policy*, vol. 125, pp. 1–3, Feb. 2019, doi: 10.1016/j.enpol.2018.10.013.
[19] European Statistics-Eurostat, "Early estimates of CO2 emissions from energy use," May 2020.
[20] NCEP, "Estonia's 2030 National Energy and Climate Plan (NECP 2030)," *Estonia's Communication to European Commission* , pp. 7–9, Dec. 2019, Accessed: Jul. 08, 2021. [Online].
[21] D. Ciampa, R. Cioffi, F. Colangelo, M. Diomedi, I. Farina, and S. Olita, "Use of unbound materials for sustainable road infrastructures," *Applied Sciences (Switzerland)*, vol. 10, no. 10, pp. 1–3, May 2020, doi: 10.3390/app10103465.
[22] European Statistics-Eurostat, "Energy, transport and environment statistics 2020 edition," *Printed by Imprimeries Bietlot Freres, Belgium- Statistical Books*, pp. 96–99, 2020, doi: 10.2785/463410.
[23] H. Berber, K. Tamm, M. L. Leinus, R. Kuusik, and M. Uibu, "Aggregate production from burnt oil shale and CO2 – an estonian perspective," *Oil Shale*, vol. 36, no. 3, pp. 1–2, 2019, doi: 10.3176/oil.2019.3.05.
[24] I. Karlsson, J. Rootzén, and F. Johnsson, "Reaching net-zero carbon emissions in construction supply chains – Analysis of a Swedish road construction project," *Renewable and Sustainable Energy Reviews*, vol. 120, pp. 1–5, Mar. 2020, doi: 10.1016/j.rser.2019.109651.
[25] Sven Sillamäe, Rauno Leppik, and Ando Pärtel, "Construction of forest road No 9300538 Taarikõnnu road and forest road No 9300506 Rahigu tee stabilised with oil shale ash- Taarikõnnu tee(ENG VER)," 2020.
[26] Harri Hiisjarv, "RECONSTRUCTION PROJECT FOR RAHINGU ROAD," 2020.
[27] Sven Sillamäe and Rauno Leppik, "Forest road No. 9300538 Taarikõnnu tee km 0,0 – 1,260 construction of oil shale ash stabilised cover- Tehniline kirjeldus (ENG VER)," 2020.
[28] S. Mozaffari, O. Järvik, and Z. S. Baird, "Effect of N 2 and CO 2 on shale oil from pyrolysis of Estonian oil shale," *International Journal of Coal Preparation and Utilisation*, pp. 1–5, 2021, doi: 10.1080/19392699.2021.1914025.
[29] T. Hain *et al.*, "The composition and properties of ash in the context of the modernisation of oil shale industry," *Oil Shale*, vol. 38, no. 2, pp. 1–4, 2021, doi: 10.3176/oil.2021.2.04.

[30] K. Pactwa, J. Woźniak, and M. Dudek, "Coal mining waste in Poland in reference to circular economy principles," *Fuel*, vol. 270, pp. 1–4, Jun. 2020, doi: 10.1016/j.fuel.2020.117493.
[31] Y. Zhang, L. K. Korkiala-Tanttu, H. Gustavsson, and A. Miksic, "Assessment for sustainable use of quarry fines as pavement construction materials: Part I-description of basic quarry fine properties," *MDPI- Materials*, vol. 12, no. 8, pp. 2–4, 2019, doi: 10.3390/ma12081209.
[32] Minister for Economic Affairs and Infrastructu, "Transport Program-2020 to 2023," pp. 1–16, 2020.
[33] Majandus Ja Kommunikatsiooni Ministeerium, "Transport and Mobility Development Plan 2021-2035," pp. 5–10, 2021.
[34] R. Galanti, A. Cho, A. Ahmad, and T. Radovich, "Soil amendments and soil profiling impact on macadamia growth and yield performance," *HortScience*, vol. 54, no. 3, pp. 1–3, Mar. 2019, doi: 10.21273/HORTSCI13572-18.
[35] Wirtgen GmbH, "Soil Treatment Base Layers with Hydraulic Binders," 2019.
[36] STREUMASTER Maschinenbau GmbH, "High-precision, highly efficient binder discharge Binding agent spreader SW 12 MC | SW 16 MC | SW 20 MC," *Partner of Wirtgen*. pp. 4–9, Accessed: Jul. 21, 2021. [Online].
[37] "WS 250 Recyclers and soil stabilizers | Wirtgen." https://www.wirtgen-group.com/ocs/en-ee/wirtgen/ws-250-81-p/#technical-data (accessed Jul. 21, 2021).
[38] "WIRTGEN Wirtgen Spreader SW16MC recycler for sale Germany Bell, ZL13457." https://machineryline.com/-/sale/recyclers/WIRTGEN-Wirtgen-Spreader-SW16MC--17092516155930178100 (accessed Jul. 21, 2021).
[39] A. G. Mahardika *et al.*, "Analysis of Soil Compaction using Proctor Standards in Highway Construction Design," *Journal of Physics: Conference Series*, vol. 1933, no. 1, p. 012084, Jun. 2021, doi: 10.1088/1742-6596/1933/1/012084.
[40] P. Milczarski *et al.*, "Carbon Footprint Calculation and Optimization Approach for CFOOD Project," Poland, 2019.
[41] A. Parviainen, E. M. Papaslioti, M. Casares-Porcel, and C. J. Garrido, "Antimony as a tracer of non-exhaust traffic emissions in air pollution in Granada (S Spain) using lichen bioindicators," *Environmental Pollution*, vol. 263, pp. 6–9, Aug. 2020, doi: 10.1016/J.ENVPOL.2020.114482.
[42] H. Yuansheng and S. Mengshu, "What are the environmental advantages of circulating fluidized bed technology? ——A case study in China," *Energy*, vol. 220, pp. 2–11, Apr. 2021, doi: 10.1016/J.ENERGY.2020.119711.
[43] E. Croci, M. Donelli, and F. Colelli, "An LCA comparison of last-mile distribution logistics scenarios in Milan and Turin municipalities," *Case Studies on Transport Policy*, vol. 9, no. 1, pp. 2–7, Mar. 2021, doi: 10.1016/J.CSTP.2020.12.001.
[44] D. Burchart-Korol, S. Jursova, P. Folęga, J. Korol, P. Pustejovska, and A. Blaut, "Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic," *Journal of Cleaner Production*, vol. 202, pp. 6–11, Nov. 2018, doi: 10.1016/J.JCLEPRO.2018.08.145.
[45] L. Viktorovich Eder, I. Filimonova, V. Nemov, and I. Provornaya, "Forecasting Sustainable Development of Transport Sectors of Russia and EU: Energy Consumption and Efficiency," *International Journal of Energy Economics and Policy* |, vol. 8, no. 2, pp. 2–6, 2018, Accessed: Jul. 18, 2021. [Online]. Available: http:www.econjournals.com.
[46] J. Schulte and H. Ny, "Electric road systems: Strategic stepping stone on the way towards sustainable freight transport?," *Sustainability (Switzerland)*, vol. 10, no. 4, pp. 11–14, Apr. 2018, doi: 10.3390/su10041148.

[47] Alar konist, Oliver Järvik, Heliis Pikkor, Dmitri Neshumayev, and Tõnu Pihu, "Utilization of Pyrolytic Wastewater in Oil Shale Fired CFBC Boiler," *Journal of Cleaner Production*, pp. 3-undefined, Jun. 2019.

APPENDICES

Appendix 1: Midpoint Impact Category Estimated using OpenLCA

Impact category	Reference unit	Result
agricultural land occupation - ALOP	m2a	89.35595924
climate change - GWP100	kg CO2-Eq	2110.41325
fossil depletion - FDP	kg oil-Eq	573.5173077
freshwater ecotoxicity - FETPinf	kg 1,4-DCB-Eq	7.266933697
freshwater eutrophication - FEP	kg P-Eq	0.112181205
human toxicity - HTPinf	kg 1,4-DCB-Eq	242.6016281
ionising radiation - IRP_HE	kg U235-Eq	108.9388306
marine ecotoxicity - METPinf	kg 1,4-DB-Eq	8.916347788
marine eutrophication - MEP	kg N-Eq	0.430330107
metal depletion - MDP	kg Fe-Eq	21.21967059
natural land transformation - NLTP	m2	-0.576544089
ozone depletion - ODPinf	kg CFC-11-Eq	0.000278344
particulate matter formation - PMFP	kg PM10-Eq	4.14921701
photochemical oxidant formation - POFP	kg NMVOC-Eq	10.82442502
terrestrial acidification - TAP100	kg SO2-Eq	10.14427651
terrestrial ecotoxicity - TETPinf	kg 1,4-DCB-Eq	0.347250798
urban land occupation - ULOP	m2a	30.87380102
water depletion - WDP	m3 water-Eq	0

Appendix 2: End-Point Impact Categories Estimated using OpenLCA

Impact category	Reference unit	Result
ecosystem quality - agricultural land occupation	points	2.965198506
ecosystem quality - climate change, ecosystems	points	36.98405907
ecosystem quality - freshwater ecotoxicity	points	0.007076514
ecosystem quality - freshwater eutrophication	points	0.011295115
ecosystem quality - marine ecotoxicity	points	0.002238839
ecosystem quality - natural land transformation	points	0
ecosystem quality - terrestrial acidification	points	0.13001186
ecosystem quality - terrestrial ecotoxicity	points	0.120654078
ecosystem quality - total	points	41.70172314
ecosystem quality - urban land occupation	points	1.48118915
human health - climate change, human health	points	58.51340092
human health - human toxicity	points	3.78143192
human health - ionising radiation	points	0.035455123
human health - ozone depletion	points	0.015052269
human health - particulate matter formation	points	22.32384483
human health - photochemical oxidant formation	points	2.26115231
human health - total	points	86.93033737
resources - fossil depletion	points	71.17122885
resources - metal depletion	points	9.242388292
resources - total	points	80.41361714
total - total	points	209.0456776