KAUNO TECHNOLOGIJOS UNIVERSITETAS
APLINKOS INŽINERIJOS INSTITUTAS

Vaida Malijonytė

ENERGIJOS REGENERAVIMO IŠ NAUDOTŲ PADANGŲ IR PARINKTŲ KIETŲJŲ ATLIEKŲ GALIMYBIŲ BŪVIO CIKLO VERTINIMAS

Magistro darbas

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KAUNAS, 2015

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Aplinkos vadyba ir švaresnė gamyba

Studijų programa 621H17002

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KAUNAS, 2015

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Aplinkos apsaugos vadyba ir švaresnė gamyba, 621H17002

(Studijų programos pavadinimas, kodas)

„Energijos regeneravimo iš naudotų padangų ir parinktų kietųjų atliekų galimybių būvio ciklo vertinimas“

AKADEMINIO SĄŽININGUMO DEKLARACIJA

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Kaunas

Patvirtinu, kad mano, **Vaidos Malijonytės**, baigiamasis projektas tema „Energijos regeneravimo iš naudotų padangų ir parinktų kietųjų atliekų galimybių būvio ciklo vertinimas“ yra parašytas visiškai savarankiškai ir visi pateikti duomenys ar tyrimų rezultatai yra teisingi ir gauti sąžiningai. Šiame darbe nei viena dalis nėra plagijuota nuo jokių spausdintinių ar internetinių šaltinių, visos kitų šaltinių tiesioginės ir netiesioginės citatos nurodytos literatūros nuorodose. Įstatymų nenumatytų piniginių sumų už šį darbą niekam nesu mokėjęs.

Aš suprantu, kad išaiškėjus nesąžiningumo faktui, man bus taikomos nuobaudos, remiantis Kauno technologijos universitete galiojančia tvarka.

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Malijonytė, V. Energijos regeneravimo iš naudotų padangų ir parinktų kietųjų atliekų galimybių būvio ciklo vertinimas. *Magistro* baigiamasis projektas / vadovas doc. dr. Irina Kliopova; Kauno technologijos universitetas, Aplinkos inžinerijos institutas.

Kaunas, 2015. 74 p.

SANTRAUKA

Dideli kiekiai naudotų padangų yra šalinami kiekvienais metais daugelyje pasaulio šalių. Dėl aukšto anglies kiekio savo sudėtyje, naudotos padangos turi aukštą energetinį potencialą, kuris šiuo metu nėra pilnai išnaudojamas. Baigiamojo magistro darbo tikslas yra įvertinti poveikį aplinkai, kuris sukuriamas energijos atgavimo metu iš naudotų padangų ir kitų kietųjų atgautųjų kuro rūšių.

Kitos kietojo atliekų kuro rūšys su turimu energetiniu potencialu, tokios kaip kiektasis atgautasis kuras iš komunalinių atliekų bei kietasis atgautasis kuras iš kompostuoto komunalinių nuotekų dumblo kartu su biomasės atliekomis, yra įtrauktos į analizę. Energijos renegeravimas iš naudotų padangų yra palygintas su energijos regeneravimu iš pasirinktųjų kietųjų atliekų. Taip pat, įvertinta galimybė maišyti nagrinėtus atliekų kurus su naudotomis padangomis, taip siekiant pagerinti kietųjų atgautųjų kurų kaloringumą.

Tikslui pasiekti yra taikomas būvio ciklo įvertinimo metodas. Magistro baigiamąjame darbe yra pateikiami būvio ciklo vertinimo rezultatai, atitinkamai pagal sudarytus energijos regenravimo scenarijus naudojant sekančias kuro rūšis: (a) smulkintos naudotos padangos, (b) kietasis atgautasis kuras iš komunalinių atliekų, ir (c) kietasis atgautasis kuras iš kompostuoto komunalinių nuotekų dumblo, kartu su biomasės atliekomis. Pagal gautus buvio ciklo vertinimo rezultatus nustatytas tinkamiausias energijos regeneravimos scenarijus, naudojant sprendimų priėmimo, pagal daugelį kriterijų, metodą TOPSIS.

Galiausiai, darbe pristatomas labiausiai tinkamas pasirinktų kietųjų atliekų kurų ir smulkintų naudotų padangų maišymo santykis, kuris apskaičiuotas pagal daugelio kritejų analizės rezultatus. Taip pat, įvertintas energijos regeneravimo, iš kurų mišinio, poveikis aplinkai ir kurų mišinys yra palygintas su pirminėmis pasirinktomis kuro rūšimis naudojant daugelio kriterijų analizę.

Magistro baigiamasis darbas sudarytas iš trijų skyrių. Pirmąjame skyriuje pateikiama literatūros analizė naudotų padangų susidarymo ir jų tvarkymo temomis. Taip pat išanalizuotos kitos kietiejo atgautojo kuro rūšys: kietasis atgautasis kuras iš komunalinių atliekų ir kietasis atgautasis kuras iš komunalinių nuotekų dumblo. Antrąjame skyriuje aprašoma magistro baigiamojo darbo metu taikoma metodika. Darbe taikomi šie trys metodai: būvio ciklo įvertinimas, teoriniai skaičiavimai bei daugelio kriterijų analizė. Trečiąjame skyriuje pristatomi darbo metu gauti rezutatai ir jų diskusija.

Baigiamasis darbas yra parašytas Anglų kalba. Darbą sudaro 68 puslapiai, 26 paveikslai, 26 lentelės ir 2 priedai. Darbe panaudoti 61 literatūros šaltiniai.

Malijonytė, V. Life-cycle-assessment of energy recovery from end-of-life tires and selected solid waste. *Master's thesis* / supervisor doc. dr. Irina Kliopova; Kaunas University of Technology, Environmental Engineering Institute.

Kaunas, 2015. 74 p.

ANNOTATION

In many countries large quantity of waste tires is generated every year. Due to the high carbon content tires have a large energetic potential, which currently is not fully used.

Other solid waste fuels with energetic potential, such as solid recovered fuels from municipal solid waste and waste water sludge, are included in the study, to be compared with energy recovery from end-of-life tires. As well a possibility to mix end-of-life tires with other fuels, in order to increase the calorific value, is estimated.

To reach the target the life cycle assessment method is applied. Master thesis presents the impact assessment results of energy recovery from waste derived fuels according to three selected fuels scenarios: (a) shredded end-of-life tires, (b) solid recovered fuel produced from municipal solid waste, and (c) solid recovered fuel produced from pre-composted sewage sludge combined with biomass residues. Using the given results, most preferable energy recovery scenario is determined, by applying multi-criteria analysis method TOPSIS.

Moreover in the thesis, feasible composition for selected solid fuels mixing is estimated in accordance to results, given by TOPSIS method. Environmental impact and order preference, of mixed fuel is compared to the selected main three scenarios.

Overall, thesis consists of three chapters. In the first chapter literature analysis is conducted on end-of-life tires generation and waste tires management pathways. As well literature analysis includes review of other selected solid fuels: refuse derived fuel and solid recovered fuel, including solid recovered fuel from municipal solid waste and municipal waste water sludge. In the second chapter, methodology selected for the thesis development is described. Three methods are selected: life cycle assessment, theoretical calculations, multi-criteria analysis. Third chapter presents results conducted in the thesis and discussion on the results.

The thesis is written in English. It consists of 68 pages, 26 figures, 26 tables and 2 appendices. 61 sources of literature have been used in the development of the thesis.

SUPERVISOR`S TASK

The aim of the thesis is to assess the environmental impact and the potential benefits in a gate-to-gate life cycle approach to convert refuse derived fuel from end-of-life tires and mixed municipal waste into thermal energy.

The tasks for achieving the aim are as follows:

- to conduct an analysis of the available scientific literature with respect to energy recovery from waste, management of various waste types and methods applied for assessment of impacts caused by waste-to-energy processes;
- to identify and develop several scenarios for fuel production from waste;
- to finalize exhaustive Life Cycle Inventories necessary to evaluate the overall impact of the developed scenarios;
- to assess and compare the environmental impacts of the developed scenarios by using the life cycle assessment (LCA) approach through the use of a LCA modeling software;
- to assess, compare and score the overall impact of the developed scenarios by using the multi-criteria analysis;
- to discuss the obtained results and make conclusions on the outcomes of the study.

Supervisors: Dr. sc. ing. Elīna Dāce
Dr. sc. ing. Francesco Romagnoli

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Abbreviations

ELT	End-of-life tires
RDF	Refuse derived fuel
SRF	Solid recovered fuel
MBT	Mechanical-biological treatment
MSW	Municipal solid waste
NR	Natural rubber
SBR	Styrene-butadiene rubber
BR	Butadiene rubber
PCT	Passenger car tires
TT	Truck tires
BCT	Bicycle tires
GCV	Gross calorific value
wt. %	Percentage of weight
LCA	Life cycle assessment
PAA	Polycyclic aromatic hydrocarbons
EIA	Environmental impact assessment
TOPSIS	Technique for order preference by similarity to ideal solution

INTRODUCTION

End-of-life tires are a non-degradable waste, which is generated annually in large amounts all over the world. ELT management systems differ in each country, depending on the development of a country's waste management infrastructure, implementation of innovative technologies and other impacts. As Europe has stepped forward and banned ELT landfilling, new pathways for management of ELT have to be explored.

Looking from the perspective of the waste management hierarchy, the following step after landfilling is energy recovery. It has been applied for many years already: ELT have been incinerated in dedicated incinerating plants or cement kilns. Such parameters as high calorific value of the tires' rubber make it an attractive fuel for energy recovery.

Municipal solid waste is another material which has a growing potential for energy recovery. Due to updated national waste plans, Baltic States are opening mechanical waste sorting facilities, where refuse derived fuel (RDF) or solid recovered fuel (SRF) can be generated, when recyclable materials and biodegradable waste are separated from the waste flow. Calorific value of this fuel changes, as it depends mostly on municipal solid waste composition, which varies by the country and region.

Furthermore, sewage sludge is a material that can be used for SRF production. Sludge is generated in growing amounts, as new modern waste water treatment plants are being opened. The typical use of sewage sludge is for land reclamation, but this process can be done only once in a while because of various chemical elements found in the sludge. Quality of sludge must conform to set values and standards, so not all the produced sludge is suitable for application on land. Meanwhile, disposal in landfills would create greenhouse gas emissions. Thus, other solutions for utilization of sludge must be found.

The aim of the thesis it is to asses an environmental impact and the potential benefits generated during the gate-to-gate life cycle of preparation of the end-of life tires and solid recovered fuels from selected waste for energy recovery.

To reach the aim following tasks were set:

- to conduct scientific literature analysis on energy recovery from selected waste, as well, by estimating the environmental impacts for selected three scenarios using LCA and theoretical calculation methods;
- to develop energy recovery scenarios using following fuels: (a) shredded waste tires, (b) solid recovered fuel produced from municipal solid waste, and (c) solid recovered fuel produced from sewage sludge combined with biomass residues;
- to assess and compare the environmental impacts of the developed scenarios by using the life cycle assessment (LCA) approach through the use of a LCA modeling software;
- to assess, compare and score the overall impact of the developed scenarios by applying multi-criteria analysis method TOPSIS;
- to estimate a feasible selected waste fuels mixing composition and create additional scenario (d) and compare to the main scenarios, by applying previously used LCA and TOPSIS methods;
- to discuss the obtained results and draw conclusions according to the results calculated in the thesis.

1. LITERATURE REVIEW

1.1. End of life tire generation worldwide

Every year approximately 1.5 billion units of end-of-life tires are generated globally (IRSG, 2010, cited by ERTMA, 2011). European tire and rubber manufacturer association reports that recovery rates for end-of-life tires (ELT) have been increasing since 1994, all over the world, especially in Europe, where recovery rate increased by 70%. The big growth in recovery rate was brought by introduction of Council Directive 1999/31/EC, in which restrictions for landfilling were introduced and whole tire landfilling was prohibited in 2003, shredded tires in 2006. The increase in recovery rates between year 1999 and 2010 are shown in Fig.1.1. From the figure can notice that in 2010 Baltic States fall in the category where recovery rates do not exceed 90% and is below the selected countries average recovery rate 96%. This shows us that in Baltic's ELT recovery potential is not used enough and needs improvement.

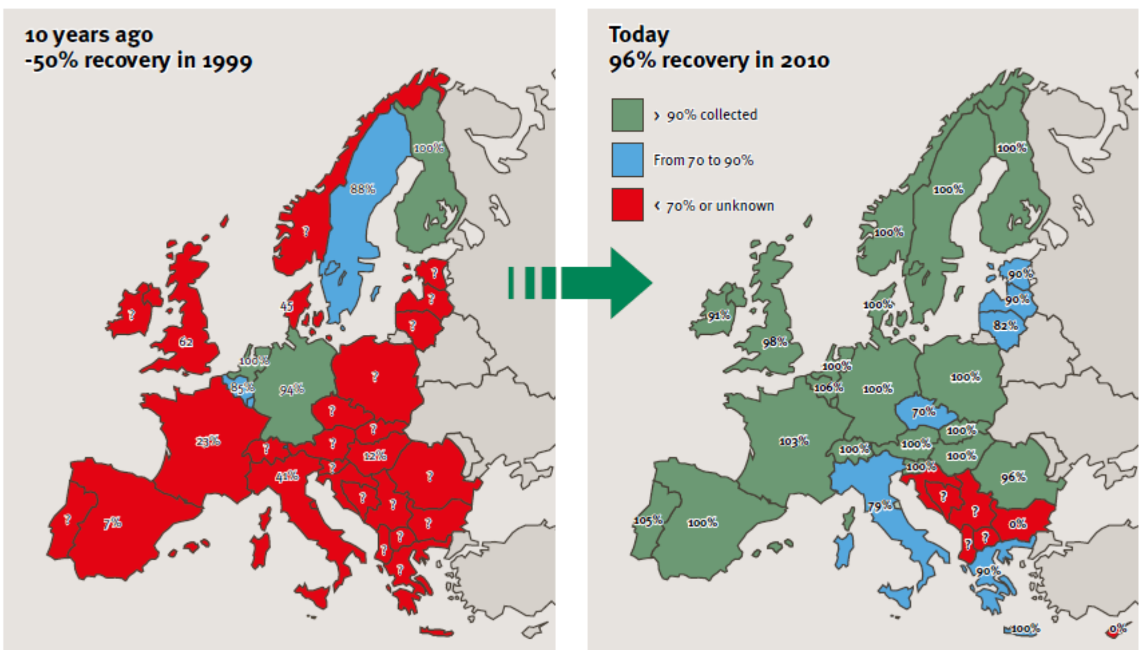


Fig.1.1. ELT recovery rates in 1999 and 2010 (ERTMA, 2012)

1.2. End of life tire generation and management situation in the Baltic States

According to ERTMA (2012) in Estonia, Latvia and Lithuania in 2010, 10, 10 and 11 kt of tires were managed, respectively. All three Baltic States have implemented producer responsibility scheme for used tires management, what means that tire producers and importers are responsible for management chain organisation (ETRMA, 2012).

Environmental Agency in Lithuania represents that in 2010year was generated 16.6kt of ELT, only<1% was exported, and the rest were used for energy and materials recovery or withheld, what in total gives us that recovery rate reaches 96%, although not taken into account the possibility of illegal ELT landfilling. In comparison to the latest data, in 2012, 20.1 kt of ELT were generated, of which 56% were recycled, 1% exported and 43% used for energy recovery. This shows that over two years the recovery rate has increased. Visible tendency is that ELT recycling is a slightly more preferable option in the country, although energy recovery has very similar results. At the moment in Lithuania there is cement kiln AB “Akmenės cementas“, where tires are incinerated together with other fuel. Cement kiln in 2012 used 43% of generated annual amount of tires for energy recovery. As well in country currently operated three tire recycling companies, which recycle 53% of generated tires in 2012.In recycling facilities tires are shredded and metal and textile materials are separated, rubber powder is used for manufacturing of roads, sports fields and supports, or sold together with scrap metal.

Latvia has a cement kiln SIA “Cemex”, where ELT are used as fuel. In2012 in this kiln 10.8 kt ELT were incinerated (SIA „CEMEX”, 2013), and almost 13 kt in 2013 (Meteo.lv, 2015). Recently in 2013 a first pyrolysis plant in Baltic’s was opened in Latvia SIA “E Daugava”, with capacity of 5 t per day. Plant is producing common pyrolysis products such as liquid fuel, gaseous fuel, technical carbon and scrap metal from tire’s cord (BNN, 2013); all products are being sold in fuel markets.

In Estonia tires are shredded and used for landfill construction. No other recovery technologies have been implemented on a large scale.

1.3. Refuse derived fuel and solid recovered fuel generation

Lithuania is soon to open nine mechanical-biological treatment (MBT) facilities, which will serve for the whole country. In the country there is one waste incineration plant in operation, where refuse derived fuel (RDF) and solid recovered fuel (SRF) could be possibly incinerated. Expected received MSW composition is given in Table 1.1. In the table Lithuanian MSW composition is compared to other countries MSW compositions.

MBT plants are equipped with mechanical sorting lines and biological treatment facilities, it is expected that plants will generate 3 types of outputs after mechanical sorting: recyclable materials (metals, plastics, paper, glass), SRF and inert waste. The expected amount of recyclables is 12-18%from whole MSW mass flow (Sweco, 2014). SRF is expected to be 30-45% from received waste mass, what will consist of sorted out MSW18-20% of the MSW flow is expected to be inert and other waste, which will be directed to landfill and the rest part of waste flow will be treated biologically.

The remaining materials, about 30%, are treated biologically and compost is generated, in specific cases alternative energy is produced. After biological treatment remaining compost biomass can be a part of produced SRF, which can form till 40% of whole SRF. In the plant produced SRF will be pressed in briquettes or powdery shape. In Lithuania it is planned to open in total 9 MBT plants and 1 mechanical sorting plant. The amount of treated MSW is expected to be about 1.3 kt per year.

Waste incineration plant UAB “Fortum Klaipėda“, in Lithuania, Klaipėda district has been opened in 2013. Plant has capacity of 50 MW heat productions and 20 MW of electricity. During 2014 in plant have been incinerated 141 kt of municipal and industrial solid waste together with 135 kt biomass waste. Due to new licenses gained in 2015 to incinerate waste from all over the country, next year it is expected to increase incinerated waste amount till 180 kt per year (Delfi, 2015). The plant has advanced emission monitoring and a modern gaseous emissions cleaning facility, which leads emissions to be lower than EU limits.

At the same time Estonia is planning to open in total four MBT plants (European Environmental Agency, 2013). While only about 30% of municipal waste gets sorted, more than half of the flow remains unsorted (Eesti Energia, 2014). This is the reason why country is focusing as well on mass-burn waste incineration as an alternative for municipal solid waste treatment (Moora, 2012), as it is reasonable to produce energy than landfill the unsorted waste (Eesti Energia, 2014). As a result power plant, where heat and power are produced during waste incineration, has been opened in 2013 near Tallinn (Eesti Energia, 2014). In 2014 the plant has produced 248.1GWhand 111.8 GWh of heat and electricity respectively, using 221.4 tones of mixed municipal solid waste (Eesti Energia Corporate Social Responsibility Report, 2014).

Table 1.1.Expected MSW composition (waste as received wt. %)

Waste fraction	Lithuania	Latvia	Estonia	France
Food waste	36,8	59	30	21
Paper and cardboard	22,6	10	17,53	36
Plastic	17,3	11,5	18,63	7
Textile	1,1	4,4	4,43	5
Wood waste	1,1	2,2	0,44	4
Green waste	5,4	-	6,65	6
Glass	9,7	5,5	8,32	11
Metals	2,8	3,9	2,58	5
Other fractions	3,0	3,6	11,42	5
Source	39	44	45	40

In Latvia, ten MBT facilities have been set into operation. The primary aim of the MBT plants is to do pretreatment of wastes prior to their landfilling. Though, as a secondary target generation of RDF is considered. At the moment in the country is no waste incineration plant, except a cement kiln. Furthermore, according to the State Waste Management Plan of Latvia, no waste incineration plants are to be built at least until 2020, although construction of a waste incineration plant has been considered (Aleksic, 2013).

In an MBT plants built in Lithuania, unsorted waste flows are being sorted out: recyclable material flows are separated and directed to recycling facilities, biological waste is treated using composting or anaerobic digestion and the residual waste stream is compressed and used as SRF for energy recovery, or landfilled. The quality of SRF varies depending on such factors as composition, humidity and other characteristics.

Technically amounts of generated RDF and SRF will be higher, when all MBT plants will be in operation Baltic’s. As it is known, RDF is a low quality fuel to be incinerated alone; therefore a solution would be to mix RDF with other type of fuel or waste, which has a higher calorific value.

SRF can be produced from other waste materials, such as sewage sludge, produced in waste water cleaning plants. According to the Eurostat data, in EU-27 sewage sludge is landfilled (21% of the total amount), incinerated (10%), applied to land (45%) and treated in other ways (24%) (Kliopova and Makarskienė, 2015). This means that 10% of total generated sewage sludge is used for SRF production. However, in Lithuania only 40% of sewage sludge is treated, while the rest part is landfilled, accumulated or exported. As more than half of the material is not treated, sewage sludge has a potential to be used for SRF production

1.4. Sewage sludge production and characteristics

Waste water treatment plants received raw waste water in first stage cleans mechanically; second stage is biological treatment (Houdkova et al., 2008). During both treatment stages, sewage sludge is produced, which is usually used for biogas recovery by using anaerobic processing (Kliopova and Makarskienė, 2012). In Lithuania during 2012 year was produced above 45 kt of sewage sludge (AAA, 2014). Produced sewage sludge treatment is a remaining issue not only in Lithuania and other Baltic states, but in the whole Europe (AAA, 2014).

Typical sewage sludge processing scheme is given in Fig. 1.2. Aerobic digestion as well can be used for sludge stabilization (Houdkova et al., 2008); although during anaerobic sludge processing produces biogas, which is used for energy production. Usually waste water treatment sludge is used for agricultural application, used for making compost, land reclamation and thermal utilization (Werle and Wilk, 2010). Due to heavy metals and other potential hazardous materials, found in sludge, it becomes a difficult process how to utilize it (Zabaniotou and Theofilou, 2008).

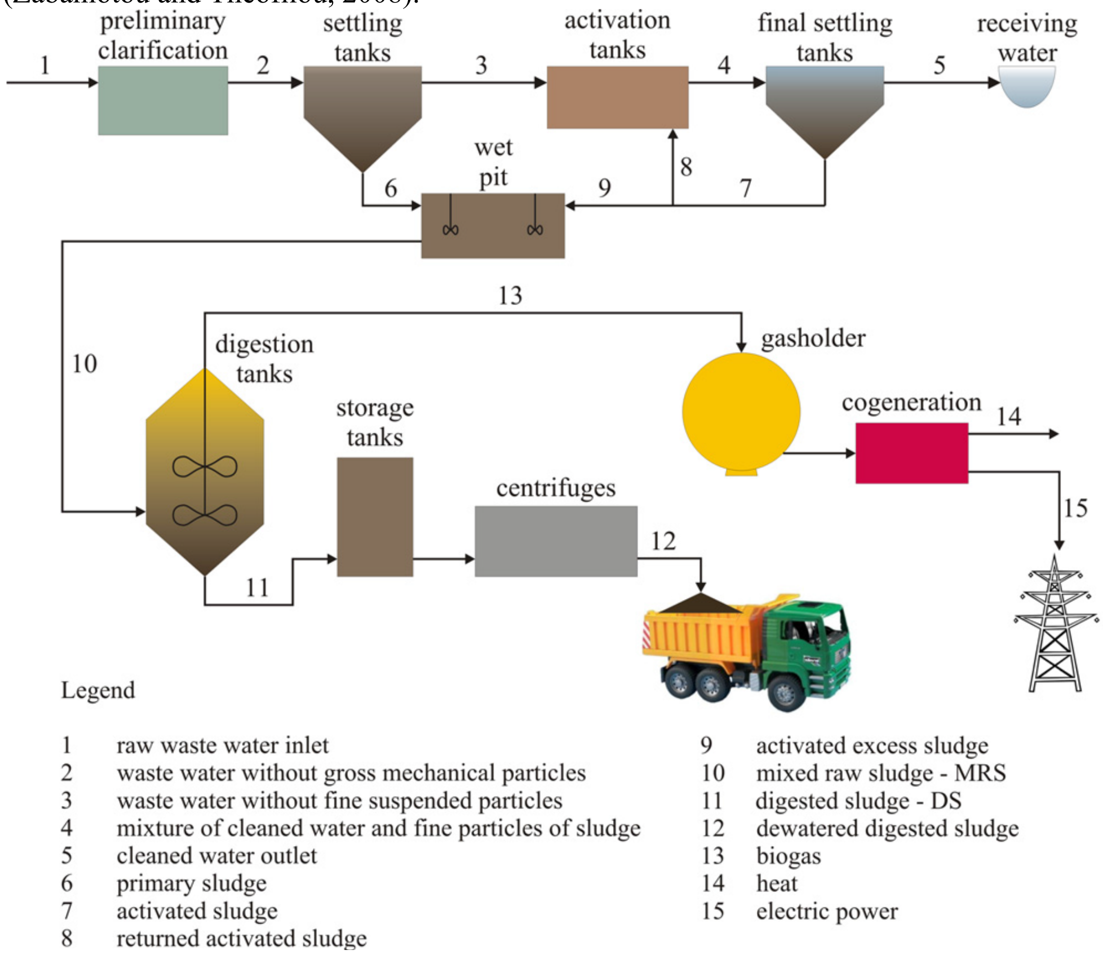


Fig.1.2. Typical waste water treatment plant scheme (Houdkova et al. 2008)

Thermal utilization methods are said to be a promising alternative for sludge use (Werle and Wilk, 2010). Thermal utilization includes pyrolysis, gasification and combustion methods. Combustion can be carried for sludge fuel alone or mixing it together with other fuels, such as lignite, wood or municipal waste. It can be done in various power plants, thermal plants and cement kilns. Zabaniotou and Theofilou (2008) carried out a study on possibility to combust sewage sludge in cement kiln together with coal

Kliopova and Makarskienė have carried out several studies on possibilities to produce SRF from sewage sludge mixed with green biomass residues, generated in public areas. In the first study (Kliopova and Makarskienė (ENERCOM), 2012) the SRF was produced from sludge pre-composted with green biomass residues and mixed in various ratios with sawdust and peat. Important to notice, that sewage sludge was used from waste water treatment situated in Luxemburg. Final fuel was processed in pellets and briquettes forms, although pelleting requires more energy. Given conclusions stated that SRF can be produced only from separated fraction (10-40 mm) of pre-composted materials (sewage sludge and biomass residues), without sawdust or peat addition, what was carried out in the second study (Kliopova and Makarskienė, 2013). The net calorific value of such produced SRF (with 10 % of moisture content) is 13-15 MJ/kg. For example, SRF, produced in Lithuania, contributes to class 4 by the net calorific value (14.25 MJ kg-1) according to the SRF Classificatory CEN/TC 343, to class 1 by the chlorine content in dry matter (0.016%) and to class 3 by mercury content (0.042 mg MJ-1) (Kliopova and Makarskienė, 2015).

Table 1.2. Physical and chemical parameters of sludge (Content in dry matter, %)

Analyzed parameters	Sewage sludge		Stabilized sludge	
	Lithuania, Palanga (Kliopova, 2012)	Luxemburg (Kliopova and Laurinkevičiūtė, 2009)	Luxemburg (Kliopova and Makarskienė, 2012)	Lithuania, Palanga (Kliopova and Makarskienė, 2015)
Ash content	44.85	53.00	30.770	20.570
Hydrogen (H)	3.93	3.50	4.340	4.580
Carbon (C)	24.93	26.00	36.320	37.380
Nitrogen (N)	4.07	3.10	1.860	2.040
Sulphur (S)	0.77	0.83	0.573	0.430
Chlorine (Cl)	0.03	0.16	0.138	1.6×10^{-2}
Cadmium (Cd)	2.0×10^{-4}	1.5×10^{-4}	1.000×10^{-4}	$1.100 \cdot 10^{-4}$
Copper (Cu)	2.51×10^{-2}	2.46×10^{-2}	1.2×10^{-2}	0.8×10^{-2}
Lead (Pb)	3.3×10^{-3}	7.9×10^{-3}	3×10^{-3}	$1.300\cdot10^{-3}$
Nickel (Ni)	1.9×10^{-3}	1.3×10^{-3}	5×10^{-3}	$0.490 \cdot10^{-3}$
Chromium (Cr)	3.4×10^{-3}	1.2×10^{-3}	9×10^{-3}	0.8×10^{-3}
Mercury (Hg)	1.4×10^{-4}	2.6×10^{-4}	0.12×10^{-3}	0.07×10^{-3}
Zinc (Zn)	8.4×10^{-2}	15.9×10^{-2}	6.5×10^{-2}	4.9×10^{-2}
Manganese (Mn)	9.4×10^{-2}	10.7×10^{-2}	5.2×10^{-2}	4.5×10^{-2}
Iron (Fe)	1.37	2.52	1.070	0.570
Calcium (Ca)	6.45	2.83	2.580	3.630
Aluminum (Al)	1.54	4.70	1.760	0.610

Table 1.3. Sewage sludge composition

	Palanga, Lithuania (Kliopova, 2012)	Vilnius, Lithuania (Statkutė and Rimeika, 2013)	Limassol, Cyprus (Zabaniotou and Theofilou, 2008)	Plant in Lithuania (Kliopova and Makarskienė, 2015)	Europe (Disposal and recycling routes for sewage sludge, EC, 2001)
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Cu	107-124	210-428	4,5	10-125	39-641
Fe	-	-	35813	-	-
Cr	18,52-24,01	84-166	31,7	18-24	16-275
Cd	1,81-3,52	1,3-9,3	1,4	1-4	0,4-3,8
Ni	12,18-22,49	68-151	35,9	12-23	9-90
Pb	15,61-23,43	25-74	18,8	15-24	13-221
Zn	872-995	597-1556	2640	800-1000	142-2000
Hg	0,2-0,41	0,8-2,3	0,4	0,2-0,4	0,3-3,0

In both studies physical and chemical characteristics of sewage sludge, pre-composted materials and produced SRF have been determined in the laboratory and compared with the legal requirements. Table 1.2 presents the information about chemical characteristics of sewage sludge and pre-composted materials in Lithuania in comparison with sewage sludge in Luxemburg.

A study in Cyprus has been carried out, by Zabaniotou and Theofilou (2008), on possibilities to incinerate sewage sludge in local cement kiln. Authors have assessed the composition of collected sludge and emissions when incinerating in cement kiln. In comparison sewage sludge composition in Cyprus (Zabaniotou and Theofilou, 2008) and composition in Lithuania (Kliopova and Makarskienė, 2015) are similar, except for such heavy metals as nickel (Ni) and zinc (Zn), which are higher in Cyprus case and cadmium (Cd) higher in Lithuanian case, see Table 1.3. Primary sludge in Cyprus had 65-70% of moisture content, in Lithuania 75-80%.

Zabaniotou and Theofilou (2008) measured gaseous emissions when incinerating sludge in the local Vassiliko Cement Plant. Authors state that sludge feed rate should be around 5% of the cement kiln capacity.

1.5. Used tire characteristics

In practice there are more than 100 different species of tires (Zabaniotou et al., 2013), as they vary because of the variety of manufacturers and their purpose, such as passenger car, heavy vehicles and bikes, bicycles. The main features are dimensions, weight, density and composition. This is because tires have to withstand different loads and have specific desired performance. As tires are different in specifications and sizes, Curry et al. (2011) give the average weight for used passenger car tire – 7.1 kg and for truck tire – 11.11 kg.

Based on Feraldi et al. (2013) tires are made of rubber material, including reinforcing layers, called plies, between layers of compounded rubber. The layers are made from metal cords, which are to give the structure for tire and withhold the tension. Rubber layers pressed together with metal cord acts as sealant. As well there are layers of textile compressed together with rubber, to support the shape of tire sides.

Tire rubber type can vary depending on producer or tire performance. However, tire manufacturers are not tended to reveal the formulations (Feraldi et al., 2013). There are several types of rubber used for tire manufacturing: natural rubber (NR), styrene-butadiene rubber (SBR) and butadiene rubber (BR), as identified by Zabaniotou et al. (2013).Barriocanal et al. (2014) also mention nitrile and chloroprene rubbers. Usually there is a rubber blend of two or three types used, involving most common styrene butadiene rubber together with additives, such as fillers, vulcanizing chemicals and softening oils (Feraldi et al., 2013). According to the author, as fillers are mostly used carbon black and silica, their purpose is to increase the mechanical strength and stiffness. As vulcanizing chemicals, mostly used sulphur or an equivalent curative, to form cross-links between individual polymer chains, what makes the product more durable. To accelerate the process zinc oxide can be used, stearic acid and anti-degradants.

Several studies have been carried out on the composition of waste tires. Zabaniotou et al. (2013) in their work collected results on composition from various authors, separating used tires by their type: passenger car tires (PCT), truck tires (TT) and bicycle tires (BCT), and compared them between themselves and to several types of fuels and materials. Feraldi et al. (2013) in their study reveal tendencies for compositions of different types of tires.

Styrene butadiene rubber (SBR) is used in larger proportions for passenger cars, while synthetic rubber is more resistant against chemical degradation. The ultimate analysis results by Zabaniotou et al. (2013), on passenger car tires (see Table 1.4.) showed the same tendency. The highest part of weight depends on coal; the rest consists of hydrogen, oxygen, nitrogen, small amount of sulphur and ash, which was found in some samples. In PCT cases where the amount of oxygen was higher, the gross calorific value (GCV) was lower, although in the rest of cases GCV is close to 40 MJ/kg.

Higher content of natural rubber than synthetic rubber is used for truck tires, which carry higher load and need higher elasticity. As well for truck tires more sulphur is added, what increases their durability (see Table 1.4.).

Table 1.4. Used tire characteristics (Zabaniotou et al., 2013)

Ultimate analysis (wt. %)														
	PCT	PCT	PCT	PCT	PCT	PCT	PCT	PCT	PCT	PCT	PCT	TT	TT	BCT
C	85,9	82,5	86,4	74,3	79,1	77,6	67,08	87,6	86	84,3	81,64	82	83,2	74,5
H	8	6,4	8	7,2	6,7	7	6,12	7,6	8,4	7,6	8,41	7,2	7,7	6,5
O	2,3	5,7	3,2	15,89	12	7,7	24,58	3,1	3,2	5,7	0,81	-	6,16	16,42
N	0,4	0,5	0,5	0,9	0,6	0,43	0,17	0,3	0,5	0,5	0,37	0,4	1,5	0,95
S	1	1,1	1,7	1,71	2,3	1,4	2,05	2,01	1,9	1,9	1,95	2,3	1,44	1,63
Ash	2,4	3,8	2,4	-	-	-	-	-	-	3,8	6,82	-	-	-
ref	21,22	25	28	29	32	33	34	35	36	38	39	41	29	27
Proximate analysis (wt. %)														
Vol.	66,5	-	62,2	58,2	61,8	71,5	59,69	63	66	-	-	-	66,2	55,2
Carb.	30,3	-	29,4	21,3	28,9	28,5	19,45	-	29,1	-	-	-	27,5	22,3
Ash	2,4	-	7,1	18,9	8,6	8,3	19,13	9,3	4,9	-	-	-	5	21
Moist	0,8	-	1,3	1,6	0,8	0,2	1,72	-	0	-	-	-	1,4	1,5
GCV, MJ/kg	40	-	40	30,5	-	36	27,37	36,74	38,3	-	-	-	33,4	28,75

For bicycle tires GCV is lower because of larger amount of inorganic materials (Zabaniotou et al., 2013). GCV values are higher than other traditional solid fuels (coal, wood, wood pellets). The highest GCV of solid fuel in Baltic's are given for coke – 29.30 MJ/kg and coal – 25.12 MJ/kg. Used tire fuel can be combined together with other fuels or burned alone.

Parallel to Juma et al. (2006) literature analysis the proximate analysis results in both cases are similar; 60 wt. % belongs to volatile organics, fixed carbon is about 30 wt. %, and ash approximately 10 wt. %. Moisture content in Zabaniotou et al. (2013) study is between 0.2 and 1.72 wt. %. Juma et al. (2006) in their work reviewed tire samples with moisture content ranging between 0.4 – 1.7 wt. %. Yet, because in some cases moisture content was zero, it is not taken into account.

Tires have been compared by its composition to coal (Table 1.5.), where can see that their composition is very similar and tires have even higher calorific value. These similarities let tires to be combusted together with coal in cement kilns and save on coal.

Table 1.5. Comparative fuel analysis (EPA, 1997)

Fuel	Composition (wt. %)							Calorific value
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	Moisture	MJ/kg
Tires	83.87	7.09	2.17	0.24	1.23	4.78	0.62	36.023
Coal	73.92	4.85	6.41	1.76	1.59	6.23	5.24	31.017

1.6. Material and energy recovery routes in Europe

According to ERTMA (2012) report, the main material recovery route is production and use of tire rubber granulate and powder; it covers 80% of recovered material amount. Steel and fabric components are removed from tires and the remaining rubber is shredded into granules. Granulate and powder can be used in manufacturing of products which include moulded rubber and for artificial turf construction. Another well applied route is whole tire usage in civil engineering applications covers 18% of recovered material from ELT, although this market is fairly small scale. For energy recovery only two methods are applied, incineration in cement industry and use for district heating. Cement industry consumes 92% in volume, while the rest is incinerated in power plants and used for district heating. Pyrolysis, gasification and termolysis are reported as emerging opportunities, as there are few large-scale plants in operation, although economic efficiency of the methods needs deeper investigations.

Since 1996 till 2010, in Europe ELT landfilling decreased by 34%, remaining only 4%, while energy recovery increased from 20% to 38%.Retreading and reuse/export changed insignificantly. Whereas, material recycling increased from 11% to 40%, is becoming most used ELT recovery method (ERTMA, 2012). Material recovery is as well more preferable route according to waste hierarchy, set by waste directive, than energy recovery. Although Curry et al. (2011) state that it is possible that specific waste streams can be managed not according to the hierarchy, when the best overall environmental impact is justified by life-cycle thinking. ERTMA (2012) reported a life cycle study (Aliapur R&D, 2010) on 9 ELT recovery methods and the given results brought them into doubts about waste management hierarchy methods. The highest positive impact was assessed for material recovery, but they are not systematically better than energy recovery, as stated in the study. In order to find the best recovery option, not only environmental impact, but as well economic viability should be considered.

Feraldi et al. (2013) carried out a study in USA on used tires' treatment options, which involved recycling and incineration in cement kilns. Both results gave a positive impact, although positive impact conducted for recycling remained greater. As well have to mention that greater impact reductions for recycling are brought by avoided impact categories from substitution of the synthetic rubber-modified asphalt and for incineration – by substituted fossil fuels in the cement kilns. This shows that results are sensitive to the avoided impacts, which depend on what products are replaced with recycled materials or in other case, what type of fuel is replaced for incineration.

Recycling of used tires prevents from certain material production. Most common recycling options are mechanical recycling including ultrasound and baro-destructive recycling technologies (Silvestravičiūtė and Karaliūnaitė, 2006).

During conventional mechanical recycling the tires are shredded into small particles and cleaned, it includes grinding and milling as well. The next step is steel removing by magnetic separation. After that separated rubber is granulated into desired size particles (Franklin Associates, 2010; Silvestravičiūtė and Karaliūnaitė, 2006).

According to Silvestravičiūtė and Karaliūnaitė (2006), during baro-destructive method application, used tires are affected by high pressure and forms "pseudo-liquefied" rubber flows; mechanical recycling using ultrasound takes place when tires are grinded in ultrasound environment, during this process tires are pulverised into 2µm size particles and metal powder is separated.

Recycled rubber is frequently used for sport surfaces and floors, as well as in civil engineering as construction or filling material and for road surfaces, while secondary materials from tire recycling such as textile and steel are usually landfilled or recycled as well

(Ferrao et al., 2008). LCA study was carried out on ground rubber production from recycled tires and the results showed that rubber powder preparation, done in recycling plant, gives the smallest part of the whole environmental impact, refining process gives about the third of the impact, while devulcanization owns about 66%, because of high energy consumption (Li, Wang, Jin, Li, 2014).

Although recycling is the most popular used tires' management method in Europe, it still faces problems in the commercialization and profit generation (Zabaniotou et al., 2013).

1.7. Energy recovery from end-of-life tires methods

1.7.1. End-of-life tire incineration

This is the most used energy recovery route in Europe for end of life tires. Tires can be incinerated in various types of incinerators, including cement kilns, heat production plants, special tires dedicated plants. Such have operated in Italy, USA and Japan (Williams, 2005).

In incinerators combustion process happens at high temperatures above 400°C, it is highly exothermic and self-supporting (Sharma et al., 2000). Produced heat in steam can be used to cover heat demand, for the production of electricity, paper, lime or steel (Sienkiewicz et al, 2012). However, produced steam (flue-gas) contains various pollutants, which needs cleaning. One of the ways of flue gas treatment is a semi-dry flue gas cleaning system. The system contains from semi-dry flue gas cleaning equipment, where quick lime and activated carbon are used as reagents; bag filter and selective non-catalytic cleaning system (UAB "Fortum Klaipėda", 2012).

In a study carried out by Lombardi and Corti, (2004) flue gas was cleaned using calcium hydroxide spray absorber and fabric filter with final scrubbing unit, as well including urea device for NO_x emission control. Spray absorber unit as well reduces amount of dioxins and heavy metals by use of activated carbon.

Depending on the type of furnace, waste tires are pre-treated respectively. Usually tires are shredded or grinded and metal is removed, as it can harm the furnace. In case of incinerating in cement kilns, no pre-treatment is needed as there are high temperatures and remaining ash is added into cement product.

Singh et al. (2009) have carried out a study on ELT rubber co-firing with coal. Experiments were carried out in down-fired combustion test facility, supplying shredded waste tire rubber (<250 μm). The study shows that tire rubber can be co-fired with coal as well low quality coals or biomass/coal co-firing scenarios. When co-firing tire rubber with coal, NO emissions reductions have been noticed.

Well known for many years and commonly applied method is tire combustion in cement kilns, where high content of heat is needed. The main advantages of ELT incineration in cement kilns are: energy recovery from waste, natural resources saving due to fuel replacement, no solid waste are generated during combustion, accessible and widely applied method.

The main fuel for cement kilns is coke and coal, so ELT with even greater GCV is a reasonable choice. Usually in cement kilns tires do not replace all commonly used fuel, but they are mixed together. It is possible to combust whole tires, as due to high temperatures complete combustion all tire components is ensured (Sienkiewicz et al, 2012). Such incineration is assessed controversially, as there are several advantages and disadvantages.

As mentioned in the study by Zabaniotou et al. (2013), the lowest estimated GCV of used tires is 27.37 MJ/kg, whereas the highest GCV is reported to be 40 MJ/kg. This allows getting high heat content, which is needed for cement drying process. Because tires have higher energy content than coal they can be a way of saving greenhouse gas emissions, as stated by Pehklen & Roy et al. (2006). Energy recovery helps to avoid use of fossil fuels, as well saves from taking up space in landfills (Feraldi et al., 2013).

Another advantage is that during combustion the remaining ash is mixed with cement powder, so no solid waste is generated. For combustion in some cement kilns tires do not have to be shredded, although usually they are shredded due to reduced transportation volume, and can be combusted with metal and textile particles altogether.

Tire combustion in cement kilns was first introduced in United States and is still widely used. Later this method was being applied in Europe, so at the moment there is a large number of cement kilns which are suitable for tire combustion.

The arousing disadvantages are: loss of materials and emissions to environment. Looking from waste hierarchy side, energy recovery is 2nd from least desirable waste management preferences, because the materials used in product are combusted although they could be recycled, what is a more preferable way. As well, energy recovery method does not reduce natural resource usage, while there is a demand for new rubber products that could be replaced by recycled end-of-life tires. Although, some LCA studies (Aliapur R&D, 2010) brought into doubt about waste hierarchy method, because the results for material recovery were not so significantly better. Another disadvantage is dangerous combustion emissions to air, if smoke is not maintained sufficiently, which includes CO_2 and polycyclic aromatic hydrocarbons (PAA).

1.7.2. End-of-life tire pyrolysis

Pyrolysis together with gasification and termolysis are reported as emerging opportunities of energy recovery, as there are few large-scale plants in operation, although economic efficiency of the method still needs deeper investigation (ERTMA, 2012).

To start with, Zabaniotou et al. (2013) did a research on energy and material recovery by using pyrolysis for used tires and noticed that pyrolysis and gasification are classified as incineration activities. It is said that “incineration plant is any stationary or mobile technical unit and equipment dedicated to the thermal treatment of wastes with or without recovery of combustion heat generated” (Zabaniotou et al., 2013), although pyrolysis is a process of energy and material recovery, which should be separated from incineration processes. The given definition for pyrolysis also states that it is a process of thermo-chemical decomposition of materials under high temperatures and without oxygen supply, what makes it different from incineration (Wikipedia, 2015). Being categorized as incineration it makes pyrolysis less socially acceptable and may be one of the reasons pyrolysis is not a widely applied recovery method for ELT.

Pyrolysis being a material recovery method still falls in the same waste hierarchy category as incineration – other recovery, although it is a non-destructive method. ETRMA is aiming to remove ELT from the list of wastes which have to be destroyed and to use them as a source of raw materials (Zabaniotou et al., 2013).In such case pyrolysis could become widely applied, together with recycling. As ETRMA (2013) reports, economic efficiency of this method is not sufficient, this is due to not well developed market of pyrolysis products, which need improvement by standardization to become more attractive.

According to Zabaniotou et al. (2013), most process of pyrolysis operates within a temperature range between 250-500 °C, without oxygen supply in special reactors. There are noticed changes in amounts of pyrolysis products, depending on pyrolysis process temperatures. As well pyrolysis is assorted as atmospheric, vacuum, catalytic, fast or slow; it depends on the pressure maintained during the process and other operation parameters applied.

During pyrolysis process materials are affected with high temperatures what causes cracking down to simpler organic compounds, which come out in three types of products: gas, oil and char. The outcome amount of products varies depending mostly on temperature and other process parameters. Based on Zabaniotou et al. (2013) study, typical material balance for used tire pyrolysis can be shared: gas yield 9-25 wt. %, liquid yield 33-47 wt. %, char yield 28-33 wt. %.

The gaseous pyrolysis products are composed of hydrogen, carbon dioxide, carbon monoxide, methane, ethane and butadiene gasses, additional can be found some amounts of propane, propene, butane and other hydrocarbon gasses (Zabaniotou et al., 2013). Pyrolysis gasses LHV is ranging between 36.0–51.0 MJ/N m^3, which is higher than natural gas in Baltic's 33.49 MJ/m^3. Because of high LHV gas is usually used in various appliances reducing the energy needs of the pyrolysis plant. The volume of produced gas depends on pyrolysis temperature, as it increases parallel to heating rate.

Liquid product includes a large variety of chemical materials, a range of aromatics and non-aromatics, as well oxygenated compounds and other compounds as toluene, xylene, styrene, etc. with low concentration. The rich composition gives oil decent energy content and lets to compare it with diesel oil. Elemental analysis carried by Zabaniotou et al. (2013) gave results that pyrolysis oil is similar to commercial oils. This proves that oil can be used for pyrolysis plant energy needs, with LHV 42.6 MJ/kg. Frigo et al.(2014)studied the possibility to use oil as a fuel in diesel engine and the results showed that diesel and pyrolysis oil mixture can be used in diesel engines.

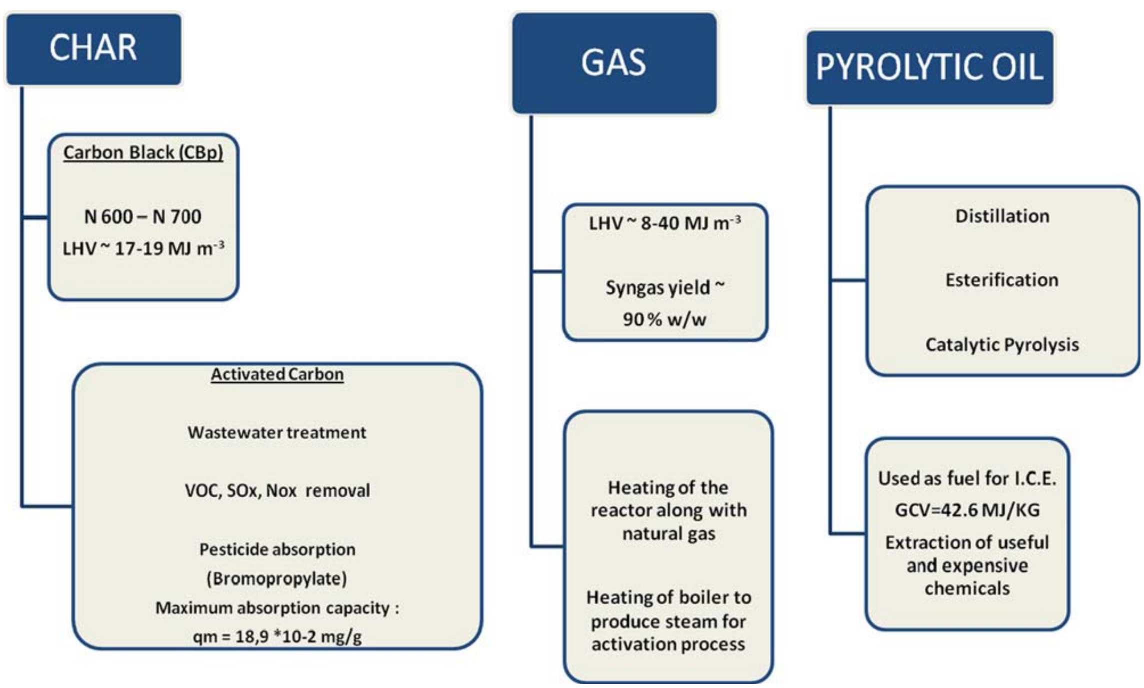


Fig.1.3. Uses of tire pyrolysis products (Zabaniotou et al., 2013)

Solid pyrolysis product called char has low commercial value, it can be further processed to acquire specific characteristics, so as to meet specifications of carbon black, or it can be used directly as it is. Char is a source of different types of carbon black, which is used in tire manufacturing, so it can be used as activated carbon or for new products' development.

Fig. 1.3 represents all pyrolysis products, with their main parameters and possibilities for use. Pyrolysis process face problems in economic viability and are not commercially successful (Ferrao et al., 2008), products as oil and gas can sufficiently cover energy needs of the plant, but char does not generate high profit, because of the poor quality.

1.7.3. End-of-life tire gasification

Gasification is another recovery method, similar to pyrolysis. The existence of oxygen in the process is the main difference of the processes. Therefore gasification is also called "indirect combustion".

During it carbonaceous materials can be converted into carbon monoxide and hydrogen based gas mixture (Donatelli et al., 2010). Part of the fuel is combusted, the produced heat is provided to gasify the rest, as well air or heat energy can be supplied during the process, depending by gasification type (Arena, 2012). As described in the book (Williams, 2005), oxygen in the form of air, steam or pure oxygen is supplied during the process, at high temperatures. Gasification occurs at higher temperatures, comparing to pyrolysis: 800-1100°C with air gasification, 1000-1400°C with oxygen gasification. Gasification reactors are classified as fluidized beds, entrained beds and fixed beds, which can be updraft or downdraft type (Williams, 2005, Donatelli et al., 2010).

During gasification only gas mixture (syngas) is produced and it does not have secondary waste (Williams, 2005). Syngas contain large amounts of not completely oxidized products, which have a calorific value, which can be used as energy carrier than can be integrated with combined cycle turbines or reciprocating engines. Oxygen gasification creates higher calorific value gaseous product than during air gasification (Williams, 2005). The produced syngas is cleaned and used as a fuel for energy recovery (Donatelli et al., 2010). However, syngas contain tars, heavy metals, halogens and alkaline compounds, which are released within the gas. Therefore syngas needs to be cleaned to meet defined specifications (Williams, 2005).

1.8. Assessment models and methods used for end-of-life tires management evaluation

There are a large number of life cycle assessment (LCA) studies, widely applied in different countries on ELT tire management. This method remains the most popular as it is standardized by ISO 14044 standard and given results are understandable, acceptable and give the possibility to compare results among various studies. As well such results are easily applicable for interested parties.

European Tyre and Rubber Manufacturers Association (ERTMA) have used LCA tool for tire waste management, carried out by R&D Aliapur, 2010. LCA compares such destructive recovery methods: cement works, foundries, steel works, urban heating, and non-destructive methods: retention basins, infiltration basins, moulded objects, synthetic turfs and equestrian floors. Study presents results on the avoided impact to one tone of ELT and results for selected eight indicators. Results gave such conclusions "It effectively appears that recycling methods do not systematically have better environmental review results than energy recovery methods." (R&D Aliapur, 2010). In this study paper (Clauzade et al., 2010) was noted the importance of increasing knowledge and methodology on end-of-life step for non-destructive recovery methods.

Similar to previous LCA study, Fiksel et al. (2011) have compared beneficial applications for scrap tires, such as ELT use as tire-derived fuel, civil engineering applications and as crumb rubber. Results showed that cement works and artificial turf production saved most GHG emissions. Cement plants as well gave good results in heavy metals reduction, air pollutants and dioxins emissions, low solid waste production. ELT use in cement plants was considered as a viable option for scrap tires utilization, as synthetic turf market is saturated.

Life cycle impact assessment method was applied to compare various waste conversion technologies (Khoo, 2009). Scrap tires gasification was included in the study and compared with pyrolysis and gasification of other waste.

Lombardi and Corti (2004) have carried out a LCA study using Eco-indicator 95' method, investigating the best option from an environmental point of view, for ELT treatment. They have compared two methods of material recovery and two of energy recovery, which were incineration as waste and incineration in the cement kiln. Energy recover methods gave better results comparing to material recovery (pulverisation process and cryogenic process).

Silvestravičiūtė and Karaliūnaitė (2006) have integrated LCA with environmental impact assessment (EIA) method, which is more suitable for issues of specific objects' analysis and less useful for assessing techniques or operating procedures.

Ferrao et al. (2000) have used a mathematical programming decision model Life Cycle Activity Analysis (LCAA), for used tire market. Method is integrating activity analysis with life cycle assessment framework.

Experiments have been carried as well, to get the results of ELT gasification. Gasification is described as one of the method to solve environmental problems and to produce energy from ELT. Karatas et al. (2013) presents experimental results of gasification of ELT with air in a bubbling fluidized bed gasifier.

Life cycle assessment method is the most frequently used method for ELT management evaluation. However another similar method has been applied in the study by Curry et al. (2011). Paper presents the research undertaken in the development of web-based decision-support tool to compare three processing routes for used tires compared to their existing alternatives. Web-based decision tool is expected to allow users to determine savings on CO_2, raw material and cost, when substituting ELT for primary materials. In the development a streamlined life cycle assessment (sLCA) approach was used as it was recommended by other authors.

This tool is said to be a much quicker and cheaper approach to assessment that allows identifying most of the issues (Kerrald, 2007). The tool creates a matrix with each member representing the adherence to the system conditions against each life cycle stage: raw materials, production, packing and distribution, use and peripherals, end-of-life. Each matrix member (presented as a colourful square) has a series of questions to ascertain the key impacts of the life cycle stage of the system conditions (Kerrald, 2007). Given questions are designed to be answered positive or negative. This tool lets to identify unsustainable aspects throughout the whole life cycle, being a more strategic and systematic approach, well suitable for product manufacturing companies.

2. METHODOLOGY

Environmental impact is evaluated by using the Life Cycle Assessment (LCA) methodology, which is widely applied for evaluation of end-of-life tire management methods. It is performed according to standard regulations ISO 14044 and using “ILCD Handbook”. Moreover, together with waste management hierarchy life cycle perspective, which systematically evaluates environmental impacts, is reported to be required (RECO Baltic 21 Tech, 2013).

For LCA special software SimaPro 8 is used. It is used for modelling and analyzing of various life cycles in a systematic and transparent way, as well to measure the environmental impact of processes across selected life cycle stages and identify the hotspots in all aspects of the chain (Pre-sustainability, 2015).

For the environmental impact generated by incineration process a theoretical calculation method is used. Full data for all scenarios of incineration process outputs is not available, therefore it is excluded from LCA study and another method is applied.

2.1. Goal and scope

2.1.1. Definition of goal and scope

The comparative LCA study is aiming to evaluate the environmental impact for energy recovery from waste tires, by incineration. For incineration process with energy recovery, three different fuel scenarios were selected: (a) shredded waste tires, (b) solid recovered fuel produced from municipal solid waste in MBT plant, and (c) solid recovered fuel produced from waste water treatment sludge and biomass. After estimating the environmental impact of selected scenarios, a model is created to estimate the most feasible composition of SRF produced from selected three fuels and scenario (d) evaluated and compared with basic scenarios.

Scenarios are selected considering current waste management situation in the Baltic’s. Countries are installing mechanical biological treatment (MBT) plants in order to reach the targets on waste management and pay more attention to waste water treatment plants, which produce sewage sludge. This study can be a helpful tool for government or waste management companies to find the most feasible solution on waste tire management methods. As well, the created model can help to find solutions for SRF and sewage sludge management.

In this study, the preference is given to the most recent data from the Baltic States. In case the local data are not available, date from other European countries are used.

Avoided products in all scenarios are not considered as in each scenario different materials are used for incineration. As well the study is aiming to get environmental impact results of each process, not taking in mind avoided products.

2.1.2. Functional unit

LCA study is comparing several energy recovery scenarios, functional unit is selected – 1 GJ of fuel input for incineration. Fuel input is an easy applicable data used for different fuels comparison and emissions calculations, not related to a specific incineration plant (Gedrovičs, 2015). Amount of recovered energy for a specific plant is possible to estimate according to fuel input data. Recovered energy amount is crucial when evaluating incineration possibilities, as it is the main product of the process. Given LCA results will provide results of the selected scenarios, with the same fuel input, generated environmental impact.

2.1.3. System boundaries

System boundaries are needed to define the system and to separate it from the other processes, which are not estimated in the study.

LCA systems have two main parts: background and foreground, where all main processes and material flows are identified.

Incineration process and its outputs are excluded from the LCA foreground boundaries as the data for incineration impact evaluation, for all the selected scenarios is not fully available. To evaluate the impact given by the incineration process, theoretical calculation method is used.

Even though incineration is excluded, for incineration process a waste CHP plant is selected. At the moment in the Baltic States there are two such plants in operation, one is situated in Tallinn, Estonia, second in Klaipėda, Lithuania, which is selected for modeling. There is 85 MW capacity furnace installed, divided between 65 MW for heat and 20 MW electricity production (UAB "Fortum Klaipėda", 2012).

In the CHP plant, fuel is incinerated and 1 GJ of fuel input is transformed into heat and electricity. As well, air emissions and ash are produced. However the LCA study is estimating only the fuel needed to produce the energy and CHP energy and electricity outputs are not evaluated.

Produced ash is landfilled. Flue gasses are treated in the waste incineration gas treating facility using semi-dry flue gas cleaning system. The system contains from semi-dry flue gas cleaning equipment, where quick lime and activated carbon are used as reagents; bag filter and selective non-catalytic cleaning system (UAB "Fortum Klaipėda", 2012).

Geographical boundaries are set to the Baltic States, as the study is aimed for this region and data is used from selected countries. This makes the results of study more applicable for Baltic States to apply in waste management planning.

The time boundaries are defined for the period over which generated impact will be considered. The used processing data is collected from period of last 5 years, considering technology changes and improvements.

2.1.3.1. Scenario A: energy recovery from ELT fuel input

For the first scenario of energy recovery from end-of-life tires, see Fig. 2.1, where processes are identified and boundaries drawn. Background system consisting of such process stages: production, packing, uses stage and collection of disposed ELT. Mentioned processes are excluded, as the study is aimed at used tires management.

Foreground system consists of processes starting with transportation to preparation facility, ELT preparation for incineration and transportation to incineration plant.

In order to prepare tires for incineration they are transported to a shredding facility, which is located in Zarasai, Lithuania. The biggest amounts of ELT are collected in the largest cities and are transported mostly from there.

In shredding facility ELT are shredded to desired size, as well metal parts are removed.

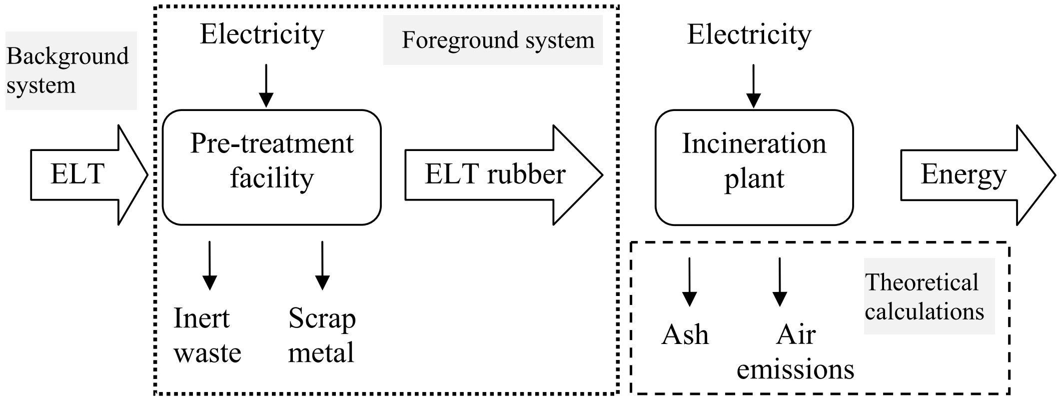


Fig.2.1. Energy recovery from end-of-life tires scheme with LCA boundaries

After shredding the remaining rubber is transported to the incineration plant. For the process selected plant is situated in Klaipėda, Lithuania. The distance between shredding facility and incineration plant is estimated.

The cut-off criteria in the system are gate-to-gate, as there is no data on background system and use of final product have various options, which are not evaluated.

2.1.3.2. Scenario B: energy recovery from SRF (MSW) fuel input

For the second scenario of energy recovery from solid recovered fuel generated from municipal solid waste, see Fig. 2.2, where processes are identified and boundaries drawn. Background system consisting of such process stages: production, packing, uses stage and collection of disposed materials. Mentioned processes are excluded, as the study is aimed at waste management.

Foreground system consists of processes starting with municipal solid waste transportation to mechanical and biological treatment facility, MSW mechanical treatment where SRF is generated, SRF preparation and SRF transportation to incineration plant.

As well as for ELT transportation, largest amounts of MSW are generated in largest cities municipalities, such as Vilnius, Kaunas or Klaipėda. MSW treatment is done in an MBT plant. For the scenario selected MBT plant is situated in Vilnius, where waste from Vilnius waste treatment region will be transported to and treated. Distance is taken as an average transportation rout in the region to MBT plant.

Mechanical municipal solid waste treatment is carried out with conveyor connected technical equipment, where detailed processes are visible in Fig. 2.2. First of all, bags of MSW are opened and recyclable materials are sorted out, the remaining flow is separated and SRF are generated, while remaining biological fraction is treated respectfully. Foreground system consists with processes during which SRF is being generated, so energy demand for biological waste treatment is not evaluated. Recyclable materials are bailed, packed and recycled. Transportation to recycling places is not estimated. Generated SRF is pressed into bales, packed and transported to incineration facility.

Transportation of SRF is estimated as a distance between the MBT plant in Vilnius and waste incineration plant in Klaipėda, which is equal to 300 km.

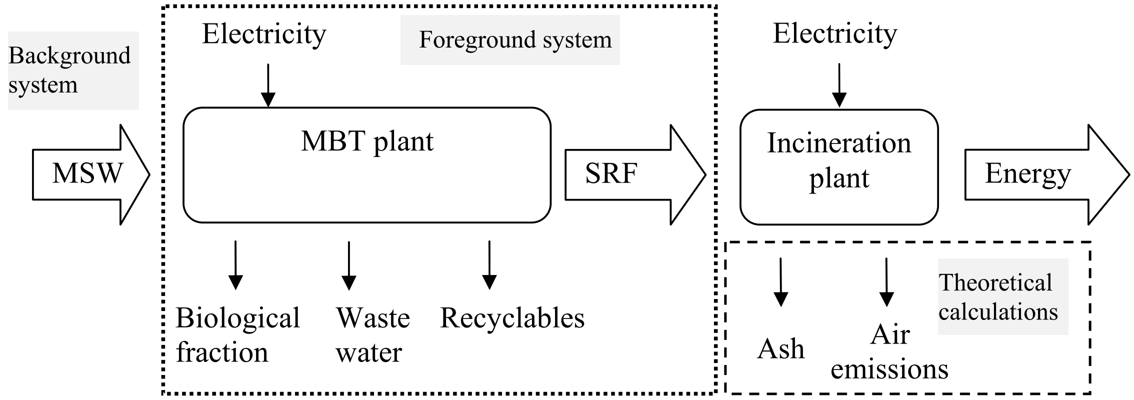


Fig.2.2. Energy recovery from SRF from MSW scheme with LCA boundaries

2.1.3.3. Scenario C: energy recovery from SRF (sewage sludge) fuel input

In the last scenario for energy recovery SRF produced from sewage sludge is used, scheme is given in Fig.2.3, where processes are identified and boundaries drawn. Background system consists of municipal waste water production and transportation via pipelines to waste water treatment plant.

Foreground system consists of processes starting with waste water treatment, where sewage sludge is produced and water cleaned.

Sewage sludge is pre-composted together with green biomass waste generated in public territories in municipality. After pre-composting, SRF is produced.

After the SRF production it is transported to the incineration plant in Klaipeda.

Final energy production is excluded from foreground system, as in the previous scenarios. The cut-off criteria in the system are gate-to-gate, as there is no data on background system and use of final product have various options, which are not evaluated.

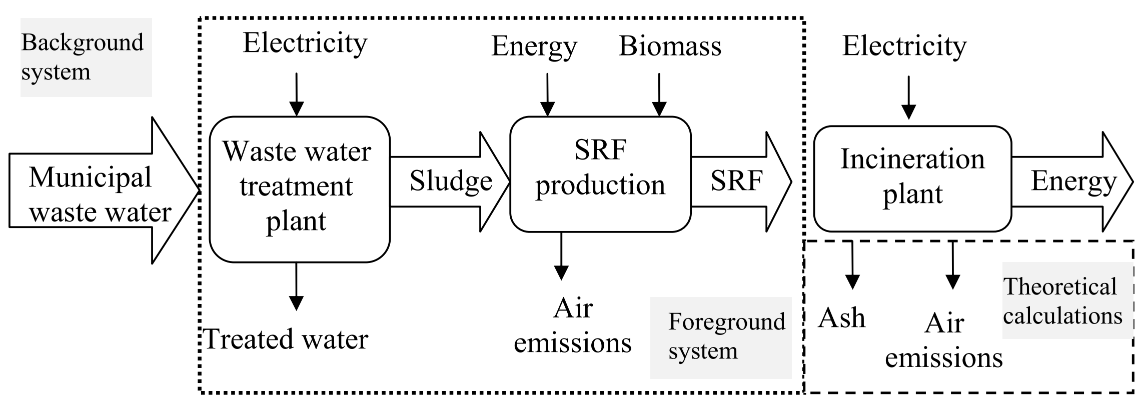


Fig.2.3. Energy recovery from SRF made of sewage sludge scheme with LCA boundaries

2.1.3.4. Scenario D: energy recovery from ELT mixed with SRF (MSW) and SRF (sewage sludge) fuel input

Scenario D is developed additionally; where energy is recovered mixing all previously estimated fuels. Energy recovery scheme is presented in Fig. 2.4.

Background system contains raw materials production, products manufacturing, use stage and disposal, waste collection.

Foreground system includes each different type of waste transportation from collection places to pre-treatment facilities. In pre-treatment facilities each type of selected waste is treated respectively and ELT rubber and SRF is produced. Produced fuel is transported to incineration plant, where energy is recovered.

All transportation distances are used the same as in scenarios A, B and C modeling, allocating only the amount of fuel transported.

As well as in previous scenarios, outputs from incineration process are excluded from LCA boundaries and amount of ash and air emissions are estimated using theoretical calculations method. Inventory data of scenario is presented in section 3.8. (Table 3.10).

Amount of each fuel used in this scenario is estimated according to the multi-criteria analysis results of fuel preference ranking (see sections 2.5. and 3.7.). Multi-criteria analysis is carried out in order to see, which of previously selected fuels is most preferable, as the best choice, and which is least preferable as the worst choice. Even the worst choice fuel is involved in this scenario, in order to use waste fuel for energy recovery and avoid its disposal.

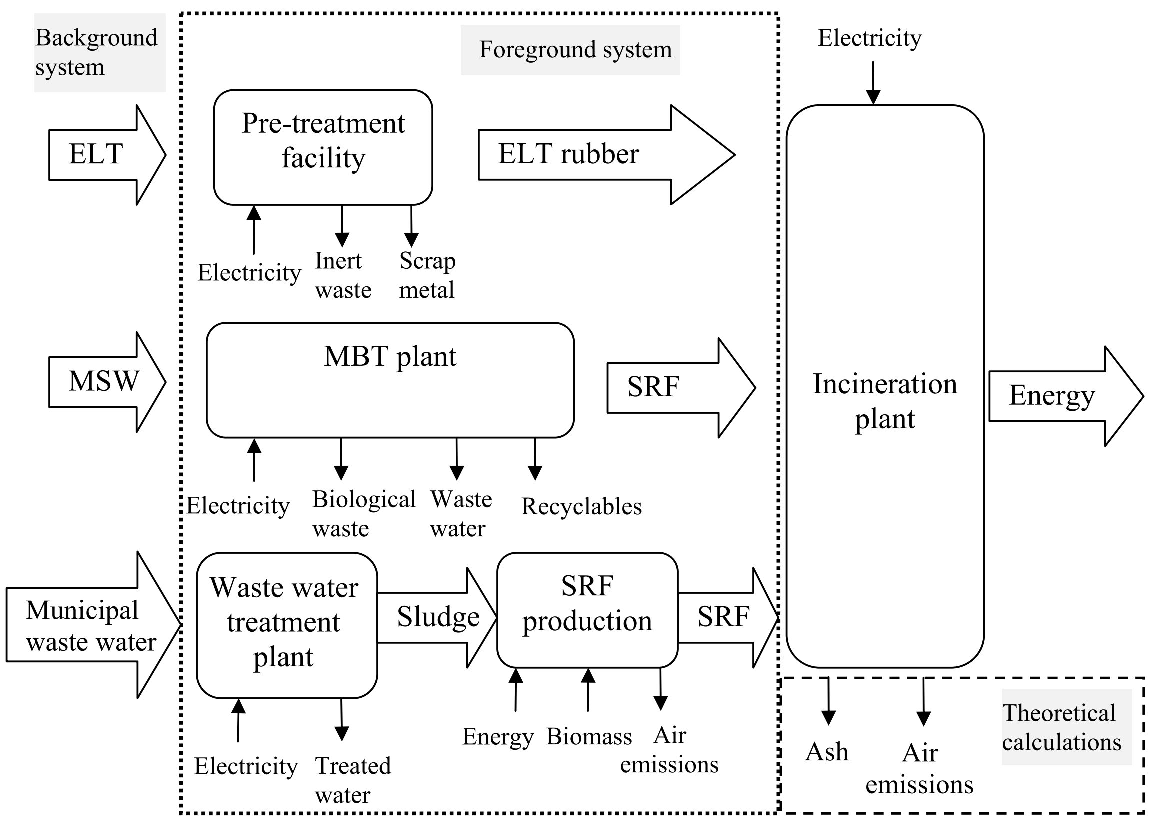


Fig.2.4. Energy recovery from fuel mix scheme with LCA boundaries

2.1.4. Assumptions and limitations

Several common assumptions and limitations are applied to all selected scenarios.

Study is limited between Baltic States, so ELT, MSW and sewage sludge are generated in one of the countries.

Evaluating transportation it is assumed that truck, after delivering each type of waste to pre-treatment facility or incineration plant, will need to come back the same distance unloaded.

Heat losses in the furnace of CHP plant are not evaluated, as incineration process is excluded from LCA study boundaries. Amount of waste fuel needed to generate 1 GJ of energy is estimated by the lower heating value of the fuel.

During the incineration three main output flows are identified, which are: recovered heat, air emissions and bottom ash. Use of final products is not included in the assessment. Amount of ash and air emissions are estimated in the theoretical calculations part.

The impact due to production of energy and goods used in the modeling, such as transport means, roads, as well fuel pre-treatment facilities and incineration plant is not included in the study.

Specific assumptions and limitations are described separately for each scenario.

2.1.4.1. Scenario A: energy recovery from ELT

ELT used for incineration are assumed to be collected in one of Baltic States. It is assumed that only PCT tires are collected and used for further processes, as they form the majority of generated ELT.

ELT collection is organized in special collection points or at tire manufacturers, sellers, where users bring used tires by themselves. Data on tire collection is not available and therefore tire collection is excluded.

Transportation from ELT collection points to shredding facility might be different in each case, as there are a lot of collecting points all over the countries. Most of the tires are assumed to be collected in the largest cities municipalities. Therefore distance is calculated as an average from the biggest cities municipalities from Lithuania (Vilnius, Kaunas, and Klaipėda) and neighboring Latvia (Riga, Daugavpils) to the shredding plant in Zarasai.

ELT are shredded and during the process inert materials, such as sand and stones, are removed, scrap metal is separated and assumed to be recycled.

Transportation from shredding facility to incineration plant is calculated as a distance between the selected plants, and is equal to 370 km one way.

2.1.4.2. Scenario B: energy recovery from SRF (MSW)

Geographical limitations are used for modeling. It is assumed that municipal solid waste is collected in Vilnius region as for estimation Vilnius MBT plant is selected.

Transportation distance to MBT plant is estimated as the average distance from furthest and closest towns situated in the region. As MBT plant is situation on the city border, waste from Vilnius city, as well will be carried some distance, which is assumed to be at least 10 km. The furthest distance measured is 52 km from Sužionys town to MBT plant. Distances from other towns to MBT plant varies between 10 km to 45 km. The average distance is estimated to be average from furthest and closest evaluated distances and is equal to 31 km.

During mechanical sorting extracted recyclable materials are recycled, but transportation to recycling places is not estimated. This is done so as to limit the study concentrating on SRF production.

All the data for SRF composition estimation, by MSW flow is limited and taken only according to Vilnius MBT Environmental impact evaluation report (Sweco, 2014). SRF is assumed to be produced only from waste remaining after mechanical sorting. Addition of SRF produced during biological digestion is not estimated in this model.

2.1.4.3. Scenario C: energy recovery from SRF (sewage sludge)

Waste water transportation to water treatment plant is done via waste water collecting pipelines. Transportation is not included in the study system as it is not possible to estimate the distance and environmental impact of transportation.

It is assumed that pre-composting facility is situated at the waste water treatment plant, or nearby to it. Therefore transportation of sludge to pre-treating facility is not included in study.

Further composting and produced compost use is not estimated in the study. LCA is limited and concentrated on SRF production and outside processes are not directly related with it.

After the SRF production it is transported to the incineration plant in Klaipėda, Lithuania. Processes were modeled using sewage sludge produced from waste water in Palanga, Lithuania, so the transportation distance of SRF is assumed as a distance between Palanga city and incineration plant.

2.1.4.4. Scenario D: energy recovery from ELT mixed with SRF (MSW) and SRF (sewage sludge)

As scenario D involves fuels estimated in previous scenarios, here the same assumptions and limitations are applied for evaluation environmental impact given by each fuel.

Transportation to incineration plant is assumed to be separate for each fuel type.

In the incineration plant fuels are mixed together and incinerated, however incineration process, as for previous scenarios, is excluded from LCA.

2.1.5. Impact categories and impact assessment method

Impact assessment method IMPACT 2002+ is selected. The method is chosen as it proposes a feasible implementation of midpoint approach, linking all types of life cycle inventory results via midpoint categories.

The results of impact evaluation are presented in midpoint and endpoint damage categories after normalization (Table 2.1).

Table 2.1. Environmental impact categories used in LCA

Midpoint categories	Damage categories
Carcinogens and non-carcinogens Respiratory inorganic Ionizing radiation Ozone layer depletion Photochemical oxidantation (respiratory organics)	Human Health
Aquatic ecotoxicity Terrestrial ecotoxicity Terrestrial acidification/nitrification Aquatic acidification Aquatic eutrophication Land occupation	Ecosystem Quality
Global Warming	Climate Change
Mineral extraction Non-renewable energy	Resources

2.1.6. Normalization and weighting

Normalization allows comparing each selected damage categories to each of it, as results are normally presented in different units. A normalized damage value represents the fractional contribution of the product system to the climate change category in Western Europe for a given time period as defined in the normalization reference, which is one year as described in IMPACT 2002+ assessment method.

Normalization is done for all damage categories, using normalization factors given by IMPACT 2002+ assessment method.

During weighting, normalized results for each impact category are assigned numerical factors according to their importance. However in this study, it is assumed that all damage categories have the same importance and weighting is not carried out.

2.2. Inventory analysis

2.2.1. Process flowchart: Scenario A

Detailed process flowchart for scenario A is given in Fig. 2.4, where background system is separated from foreground system. As well theoretical calculation modelling part is marked, as it is excluded from background system and separated from foreground, as data for all scenarios was not available. However theoretical calculations are applied to estimate amount of ash and air emissions produced.

Background system contains of such process as raw material extraction, product manufacturing, packing, transportation and use stage. Transportation of waste tires to collection places as well included in background system.

Gate-to-gate life cycle begins with transportation from waste tires collecting points to shredding facility. In the shredding facility feedstock goes to a feeding conveyor, which supplies ELT to primary rotor shredder. Primary and secondary rotor shredders are connected with belt conveyors, T^1. After the second shredder, materials that are sorted out as with too large size are transported back to secondary rotor shredder.

During shredding processes some inert waste, such as stones or sand, are generated, as they fall out from tires, what is approximately 2.8 % of the tires mass. Landfilling of inert waste is included in the boundaries. In order to remove metal chord parts, ELT are shredded one more time to the smaller size, after the process shreds are supplied by vibrating table to magnetic separator, which sorts out waste metal ("EcoIri Solution", 2015). Metal parts are estimated to be 18.16 % of the tires mass. Recycling of scrap metal is included in the foreground system.

Gate-to-gate life cycle is cut off after ELT rubber transportation to incineration plant.

Incineration process and outputs is excluded from foreground system. However air emissions and produced ash might give a significant meaning during the final results evaluation, so it is estimated using theoretical formulas. Produced heat has various possibilities of usage and it is not possible to collect all the data, so it is not included in the evaluation.

2.2.2. Data: Scenario A

Main data used for Scenario A developing is given in Table 2.2. The data is allocated for functional unit – 1 GJ of heat energy. So as to get the final data used in the life cycle assessment other necessary data was collected and calculated.

Table 2.2. Inventory analysis of scenario A

Material	Amount	Unit
End-of-life tires (ELT)	37.930	kg/FU
Transportation	Amount	unit
Transport tires (collection points to shredding facility)	9.520	tkm
Transport tires (shredding facility to incineration plant)	14.034	tkm
Processing	Amount	Unit
Used tire shredding (for incineration)	37.930	kg/FU
Input		
Lubricating oil	0.0085	kg/FU
Electricity mix	7.859	kWh/FU
Output (waste to treatment)		
Inert waste	1.062	kg/FU
Scrap metal (for recycling)	6.886	kg/FU

For the incineration used after pre-treatment remaining tire rubber characteristics are taken as an average values for PCT tires, given in Zabaniotou et al. (2013) paper, as different brand tires have specific characteristics. ELT characteristics used in the method are given in Table 2.3.

Table 2.3. End-of-life tires rubber characteristics

Fuel	Composition (wt. %)							HHV	LHV
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	Moisture	MJ/kg	MJ/kg
ELT	79.208	7.060	8.385	0.112	1.257	3.978	0	34.942	33.353

Transportation distance is calculated as an average from the biggest cities municipalities from Lithuania (Vilnius, Kaunas, and Klaipėda) and neighboring Latvia (Riga, Daugavpils) and Estonia (Tallinn) to the shredding plant in Zarasai. Distances are shown in Table 2.4.

Table 2.4. Disposed ELT transportation distances from city to shredding plant

City where ELT are collected	City where shredding plant is located	Distance, km
Kaunas, LT	Zarasai, LT	180
Vilnius, LT	Zarasai, LT	145
Klaipeda, LT	Zarasai, LT	370
Riga, LV	Zarasai, LT	240
Daugavpils, LV	Zarasai, LT	30
Tallinn, EE	Zarasai, LT	540
Average distance		251

Data used to estimate shredding facility inputs and outputs is taken from a currently working tires recycling plant. This pre-treatment method is selected, as it is easy accessible and data was available. Installed shredding facility capacity is 2.9 t/h ("EcoIri Solution", 2015).

Produced waste fuel is compared to CEN/TC 343 standard, which sets requirements for solid recovered fuel. Standard sets requirements for HHV, Chlorine and Mercury contents. However from mentioned parameters only HHV is estimated, which is 34.94 MJ/kg, what refers to 1st class fuel, as HHV ≥25 MJ/kg.

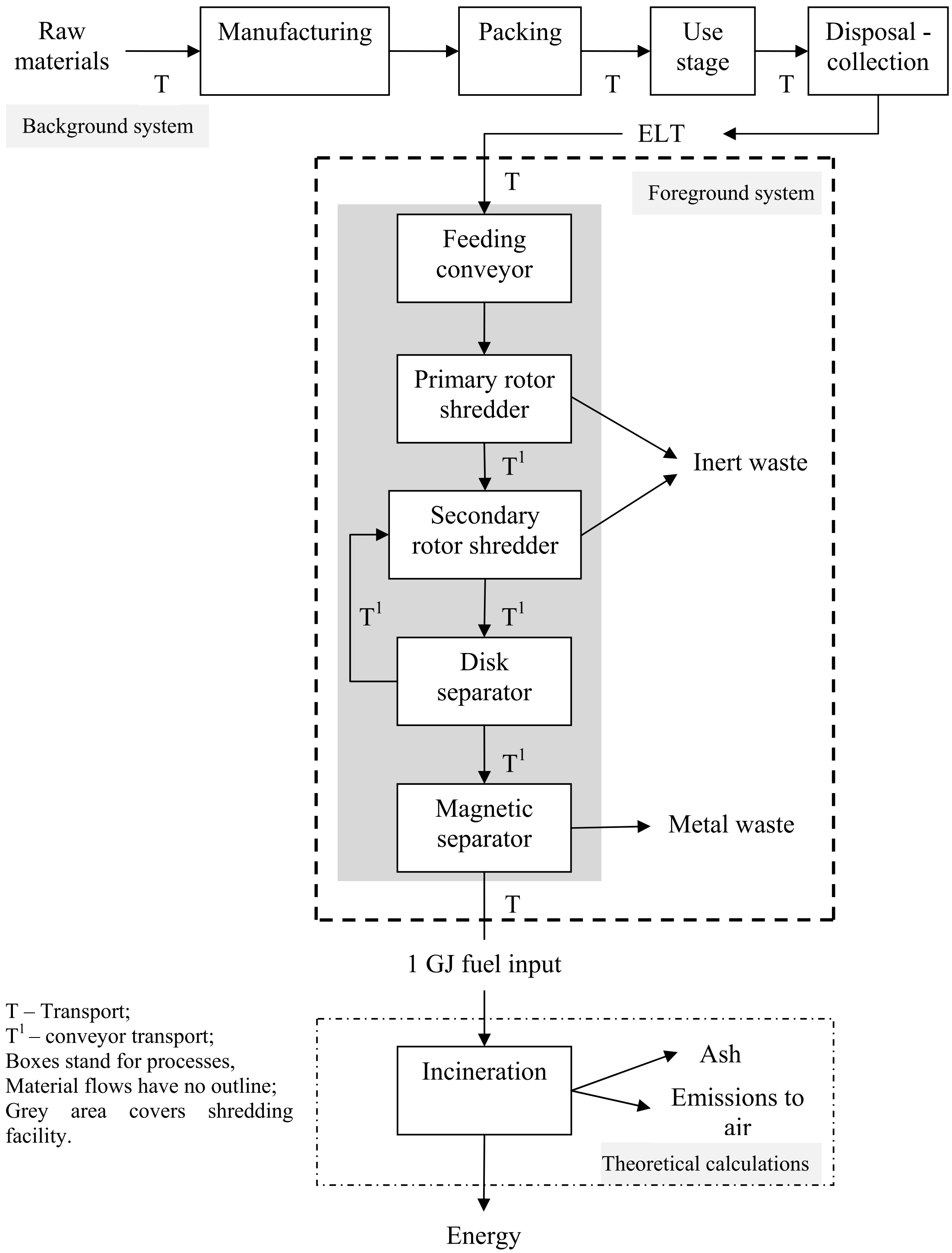


Fig.2.5. Energy recovery from end-of-life tires flowchart with LCA boundaries

2.2.3. Process flowchart: Scenario B

Detailed process flowchart for scenario B is given in Fig. 2.5, where background system is separated from foreground system. As well theoretical calculation modelling part is marked, as it is excluded from background system and separated from foreground, as data for all scenarios was not available. However theoretical calculations are applied to estimate amount of ash and air emissions produced.

Background system contains of such process as raw materials extraction, manufacturing and packing of products, transportation for users and use stage, transportation to disposal places and disposing.

As life cycle is modelled gate-to-gate, foreground systems starts at the gate of municipal solid waste mechanical and biological treatment plant, including transportation to it. In MBT plant various sorting and waste treatment processes are done. In MBT plant main waste flows are separated: recyclables (paper and cardboard, plastics, metals, glass), biodegradable waste and SRF. Recyclable materials are bailed, packed and recycled. Transportation to recycling places is not estimated. In the selected MBT plants, which is located in Vilnius, biodegradable waste is bio-dried, after bio-drying remaining materials are compacted and SRF is produced or used as compost.

However, biodegradable waste treatment after sorting is excluded from study foreground, because use of biodegraded materials has several options and there is no data for environmental impact evaluation. After solid recovered fuel from MSW is produced, it is transported to incineration plant.

As in the previous scenario, gate-to-gate life cycle is cut off after SRF transportation to incineration plant.

As well, incineration process and outputs are excluded from foreground system and included in theoretical calculations part. The use of produced heat remains in background system. It has various possibilities of usage and it is not possible to collect all the data.

2.2.4. Data: Scenario B

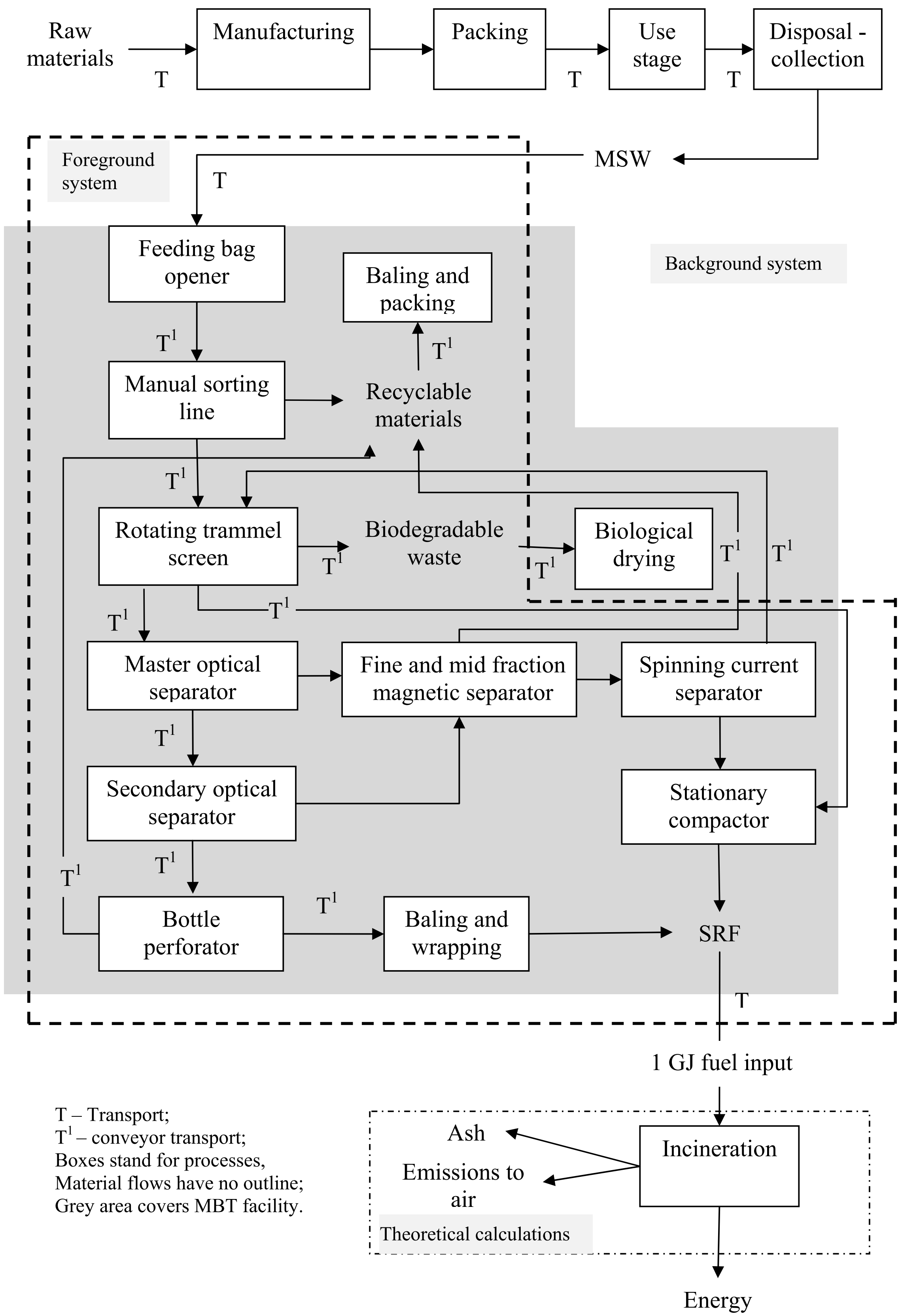
Main data used for Scenario B developing is given in Table 2.7. The data is allocated for functional unit – 1 GJ of heat energy. So as to get the final data used in the life cycle assessment other necessary data was collected and calculated.

Transportation distance to MBT estimated as average distance in the region from village to MBT and is equal to 31 km.

Data for processes happening during mechanical sorting, related inputs and outputs are used from Vilnius MBT Environmental impact evaluation report (Sweco, 2014).

Table 2.5. MSW and SRF composition

Waste fraction	MSW flow composition, %	MBT sorting efficiency, %	Remaining SRF composition, %
Food waste	36,8	100	-
Paper and cardboard	22,6	15	53,78
Plastic	17,3	45	26,64
Textile	1,1	0	3,08
Wood waste	1,1	100	-
Green waste	5,4	100	-
Glass	9,7	45	14,94
Metals	2,8	80	1,57
Other fractions	3	100	-



T – Transport;
T1 – conveyor transport;
Boxes stand for processes,
Material flows have no outline;
Grey area covers MBT facility.

Fig.2.6. Energy recovery from SRF flowchart with LCA boundaries

During mechanical sorting recyclable materials are sorted out, referring to sorting efficiency, as some materials still remain in the flow. Sorting efficiency is taken according to Vilnius MBT plant documents. Predictable composition of produced SRF is given in Table 2.5.

Table 2.6. Inventory analysis of scenario B

Material	Amount	Unit
Input		
Municipal solid waste	182.659	kg/FU
Transportation	Amount	unit
Transportation (collection points to MBT)	5.662	tkm
Transportation (MBT to incineration plant)	19.574	tkm
Processing	Amount	Unit
MSW treatment in MBT	182.659	kg/FU
Input		
Electricity mix	478.464	kWh/FU
Output (waste to treatment)		
Paper and cardboard (recycling)	6.192	kg/FU
Plastic (recycling)	14.220	kg/FU
Glass (recycling)	7.973	kg/FU
Metals (recycling)	4.092	kg/FU
Other waste not suitable for treatment (landfilling)	4.480	kg/FU

According to the remaining SRF composition, fuel characteristics are estimated. Data for characteristics of each waste type, on mass percentage on a dry basis, is used from Dominguez et al.(2003) paper. To estimate characteristics on waste as received (wet basis) formula 2.1 is used. Expected SRF characteristics are given in the Table 2.6. Higher and lower heating values are calculated using formulas 2.2 and 2.3 respectively.

$$X^r = \frac{X^d \times (100 - W^r)}{100} \quad (2.1)$$

Where:
X^r – part of material in percentage, in fuel as received;
X^d – part of material in percentage, in dry basis;
W^r – part of water in percentage, in fuel as received.

$$Q^r_{HHV} = 339 \times C^r + 1256 \times H^r - 109(O^r - S^r) \quad (2.2)$$

$$Q^r_{LHV} = 339 \times C^r + 1031 \times H^r - 109(O^r - S^r) - 25 \times W^r \quad (2.3)$$

Where:
Q^r_{HHV} – higher heating value, in fuel as received, kJ/kg;
Q^r_{LHV} – lower heating value, in fuel as received, kJ/kg;
C^r – part of carbon in percentage, in fuel as received, %;
H^r – part of hydrogen in percentage, in fuel as received, %;
S^r – part of sulphur in percentage, in fuel as received, %;
O^r – part of oxygen in percentage, in fuel as received, %;
W^r – part of water in percentage, in fuel as received, %.

Produced waste fuel is compared to CEN/TC 343 standard, which sets requirements for solid recovered fuel. However from required parameters only HHV is estimated, which is 16.59 MJ/kg, what refers to 3rd class fuel, as HHV ≥15 MJ/kg.

Table 2.7. SRF (from MSW) characteristics (fuel as received)

Fuel	Composition (wt. %)							HHV	LHV
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	Moisture	MJ/kg	MJ/kg
SRF	39.317	5.119	29.185	0.295	0.107	21.565	4.413	16.589	15.327

2.2.5. Process flowchart: Scenario C

Processes flowchart for B scenario is given in Fig. 2.6. Foreground is marked and separated from background system. As well theoretical calculation modelling part is marked, as it is excluded from background system, but estimated separately using theoretical calculations model to calculate amount of ash produced and the main air emissions.

Background system starts at municipal waste water collecting via pipe lines to the mechanical and biological treatment facility. During mechanical treatment sewage sludge is separated, remaining waste water is treated biologically and final sludge is separated from the treated water (filtrate).

As life cycle is modelled gate-to-gate, foreground systems starts at the gate of sludge pre-composting facility. However pre-composting facility is assumed to be located in the waste water treatment plant territory and transportation is not included in the foreground system. Produced sewage sludge is mixed together with biomass waste, ratio 50% and 50% respectively, and pre-composted.

After the process pre-composted materials are separated, material parts which size exceeds >40 mm are sent for further composting and compost is produced. This process is excluded from foreground system as data on further composting and use of compost is not available.

For SRF production separated pre-composted material is dried and processed in pellets. During pelleting particle matter air emissions are created, however data is not available on the air emissions and it is not included in foreground system.

Produced pellets are transported to waste incineration plant. This is the cut-off point, as in the other scenarios. Ash and air emissions generated during incineration are included in theoretical calculations model.

2.2.6. Data: Scenario C

For scenario modeling data for sewage sludge and produced SRF characteristics and energy demand for SRF production is taken from Kliopova and Makarskienė (2015) article. SRF is produced from pre-composted materials, which are sewage sludge from municipal waste water in Palanga and biomass collected in city municipality. Selected SRF production method was assessed by Kaunas University of Technology, Environmental Engineering Institute, when implementing one stage of PF7 program project “Poly generation of energy, fuels, and fertilizers from biomass residues and sewage sludge (ENERCOM)” (Kliopova, Staniškis, Laurinkevičiūtė, 2010).

The main data used for scenario life cycle assessment is presented in Table 2.8.

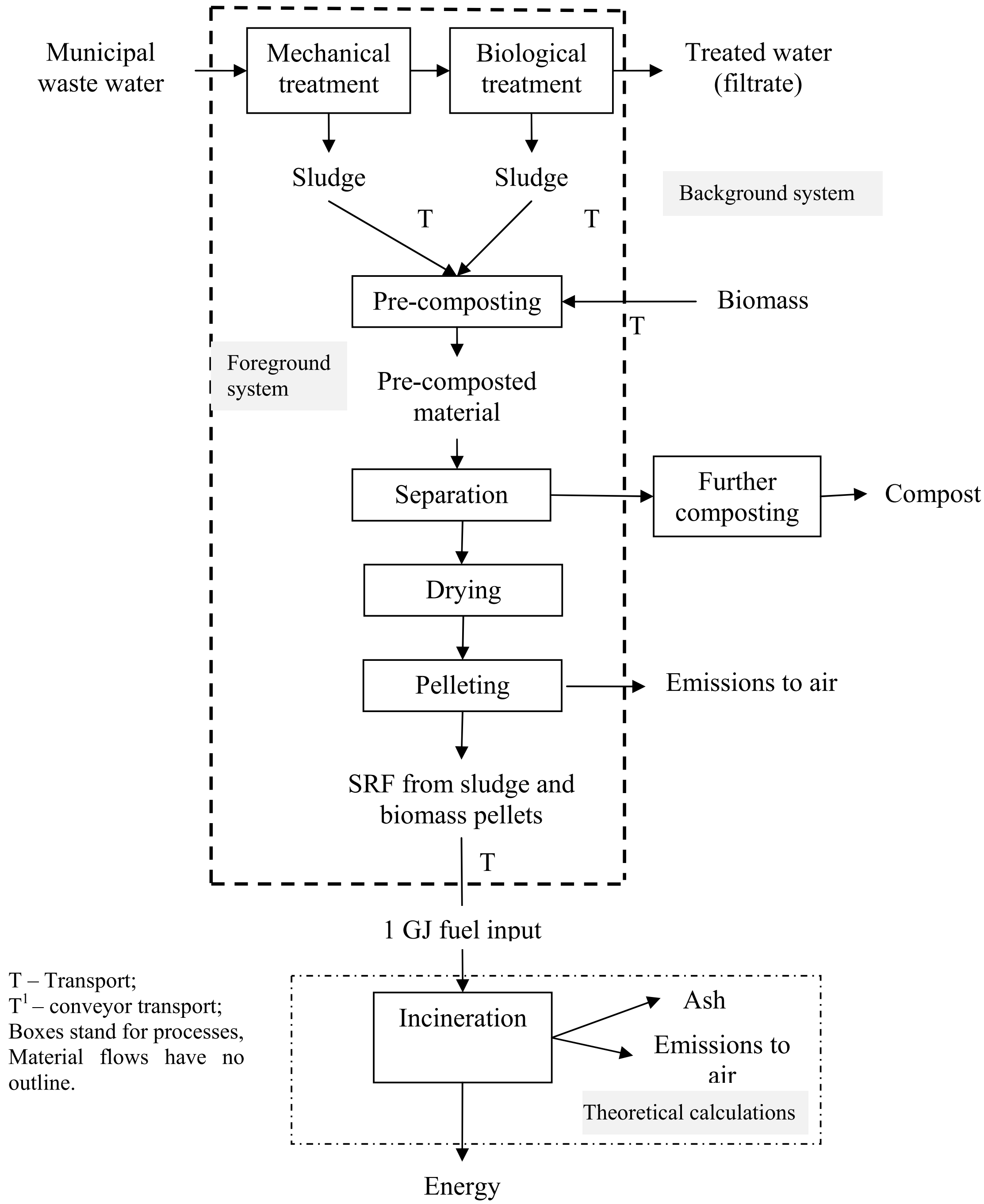


Fig.2.7. Energy recovery from SRF from sewage sludge and biomass flowchart with LCA boundaries

Table 2.8. Inventory analysis of scenario C

Material	Amount	Unit
Input		
Sewage sludge	192.221	kg/FU
Biomass waste	192.221	kg/FU
Transportation	Amount	unit
Transportation of biomass (diesel consumption)	9.227	kg/FU
Transportation (SRF production facility to incineration plant)	2.432	tkm
Processing	Amount	Unit
SRF pre-composting	384.442	kg/FU
Input		
Diesel for Residues milling, composting,	0.187	kg/FU
Water	0.038	m^3/FU
Industrial oil	0.003	kg/FU
Output		
Compost for further composting	10.841	kg/FU
Waste water	0.141	m^3/FU
Dewatering and pelleting of SRF	75.997	kg/FU
Input		
Electricity mix	0.428	kWh/FU
Water	0.038	m^3/FU
Output		
Waste water	0.038	m^3/FU
PM emissions from pelleting process	1.507	kg/FU

Composition of sewage sludge and pre-composted material is showed in Table 1.2. However data is supplied for a dry basis. After pre-composting material is dried, required water content in SRF is approximately 15% (Kliopova and Makarskienė, 2015). Therefore data is recalculated; SRF characteristics are presented in Table 2.9.

Table 2.9. SRF (from sewage sludge and biomass) characteristics (fuel as received)

Fuel	Composition (wt. %)							HHV	LHV
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	Moisture	MJ/kg	MJ/kg
SRF	31.679	4.496	18.182	2.388	1.294	26.961	15.00	14.545	13.158

Produced SRF is classified according to CEN/TC 343 standard and results are shown in Table 2.10.

Table 2.10. Comparison of SRF produced from pre-composted materials with the SRF classification system (CEN/TC 343) (Kliopova and Makarskienė, 2015)

	SRF of pre-composted materials	
	value	class
SRF shape	pellets	
HHV value as received, MJ/kg	14.54	4 (≥10)
Chlorine (Cl) content in dry matter, %	0.016	1 (≤0.2)
Hydrargyrum (Hg) content, mg/MJ (median)	0.042	3 (≤0.08)

2.2.7. Data: Scenario D

Scenario D is developed using the data from previous scenarios, as the final mixed SRF is produced from above mentioned fuels.

Process flowchart is not developed for this scenario, as processes used are the same as in scenarios A, B and C. Scheme with LCA boundaries of the scenario is given in Fig. 2.4.

Inventory analysis data is allocated according to the mixture ratio in % of each fuel. Fuel mixture is estimated using TOPSIS method, in order to find the most feasible materials mixture. Mixed fuel is taken as a homogenous fuel, which composition is estimated according the fuel composition. Data of fuel composition is given in the part of multi-criteria analysis results, Table 3.3.

2.3. Allocation

One of the main tasks during inventory analysis is to allocate data according to the system inputs and outputs (Darnios inovacijos Lietuvos pramonėje, 2010). Allocation is a boundary between the product system under consideration and other product systems (ILCD Handbook).

Inputs and outputs in the study are allocated for each scenarios separately, as they are individual and do not correlate. Outputs in processes are allocated according to the data, specified in inventory analysis, taken from literature. Selected allocation method is based on indicators of mass, volume or energy content.

2.4. Sensitivity analysis

Sensitivity check is done in order to assess the reliability of the final LCA results and effects of the variation of input parameters, by using elasticity method (Njakou Djomo and Blumberga, 2011). Sensitivity check is done for selected input data: transportation distance from waste collecting place to pre-treatment facility, transportation distance from pre-treatment facility to incineration plant, energy consumption for pre-treatment.

To carry out sensitivity analysis, selected input data is increased by 10% and the given single score result is compared with the result of the study with normal data. If the given single score result increases by ≥10%, the result is sensitive to the input data.

Sensitivity analysis results are presented in part 3.5.

2.5. Theoretical calculation method

For the environmental impact generated by incineration process a theoretical calculation method is used. Full data for all scenarios of incineration process outputs is not available, therefore it is estimated separately.

Calculations are carried out using formulas given in theoretical material and collaborating with professors.

During incineration process ash is generated as a remaining waste. Produced ash is assumed to be landfilled or treated respectively, in each scenario. The amount of produced ash is estimated according to the amount of fuel incinerated and ash content in the material, using Eq. (2.4). Data for ash calculation is given in Table 2.11. The results for each scenario are presented in section 3.6.

$$M_{ash} = \frac{M_{fuel} \times A^r}{100\%} \tag{2.4}$$

Where:

M_{ash} – mass of generated ash, kg;

M_{fuel} – mass of fuel, kg;
A^r – part of ash in percentage, in fuel as received, %.

Table 2.11. Generated amount of ash per functional unit

Fuel	Mass of fuel M_{fuel}, kg	Ash content A^r, wt. %
Scenario A: End-of-life tires rubber	29.982	3.978
Scenario B: SRF from MSW	65.246	21.565
Scenario C: SRF from sludge and biomass	75.997	26.961

Emissions are unavoidable incineration product. It was not possible to estimate the emissions in experimental way; therefore theoretical calculation model was used for evaluation. Formulas are used from theoretical material supplied by professor M. Gedrovičs (2015). In the study the main emissions are estimated: SO_2, N_2, O_2, CO, CO_2 and NO_x. All results are presented in part 3.6.

Real volume of SO_2 produced during incineration of 1 kg fuel is calculated using Eq. (2.5).

$$V_{SO2} = 0{,}0069 \times S^r \quad (2.5)$$

Where:
S^r – part of sulphur in percentage, in fuel as received, m^3/kg.

Real volume of N_2 produced during incineration of 1 kg fuel is calculated using Eq. (2.6).

$$V_{N2} = V_{N2}^o + 0{,}79\ (\alpha - 1)V^o \quad (2.6)$$

Where:
V_{N2}^o – theoretical volume of nitrogen, when α=1, calculated by Eq. (2.7), m^3/kg;
α – air excess coefficient (real case α>1, selected value for solid fuels α=1,4);
V^o – necessary theoretical amount of air, calculated by Eq. (2.8), m^3/kg.

$$V_{N2}^o = 0{,}79 \times V^o + 0{,}008 \times N^r, \text{ m}^3\text{/kg} \quad (2.7)$$

$$V^o = 0{,}0889(C^r + 0{,}375 \times S^r) + 0{,}265 \times H^r - 0{,}0333 \times O^r, \text{ m}^3\text{/kg} \quad (2.8)$$

Where:
H^r – part of hydrogen in percentage, in fuel as received, %;
N^r – part of nitrogen in percentage, in fuel as received, %;
O^r – part of oxygen in percentage, in fuel as received, %.

Real volume of O_2 produced during incineration of 1 kg fuel is calculated using Eq. (2.9).

$$V_{O2} = 0{,}21(\alpha - 1)V^o, \text{ m}^3\text{/kg} \quad (2.9)$$

To calculate volume of CO produced during incineration of 1 kg fuel it is needed to know heat losses $q_3$in the furnace due to chemically incomplete combustion. Value of q_3 normally ranges from 0 to 1.0 %, for calculations it is modeled different situations where $q_3$is increasing by 0.2 %. The final results of CO and CO_2 emissions are presented in Table 3.4, all calculations are given in Appendix 1.

Real volume of CO_2 produced during incineration of 1 kg fuel is calculated using formula:

$$V_{CO2} = 0{,}01866 \times C^r \quad (2.10)$$

Where:

C^r – part of carbon in percentage, in fuel as received, m^3/kg.

The main data used for calculations:

ρ_{CO} = 1.249 kg/m^3 (density at normal conditions);

LHV_{CO} = 12648 kJ/m^3;

LHV_{fuel} = 33353.5 kJ/kg.

Mass of NO_x is calculated using Eq. (2.11), supplied during lectures carried by professor I. Kliopova (Charkov, 1997).

$$M_{NOx} = 0{,}001 \times B \times LHV_{fuel} \times K_{NOx}(1-\beta), t \quad (2.11)$$

Where:

B – incinerated amount of fuel, kg;

K_{NOx} – parameter characterizing amount of released nitrogen oxides, during production of 1 GJ of heat energy, K_{NOx} =0.1 kJ/kg;

β – coefficient depending on nitrogen oxides emissions decreasing due to technological modifications, β=0;

LHV_{fuel} – lower heating value of the selected fuel, MJ/kg.

2.6. Multi-criteria analysis of scenarios preference and determination of fuels mixing ratio for developing scenario D

Multi-criteria analysis is selected to estimate which fuel incineration scenario is most preferable and to find closest to ideal selected fuel mixture ratio. For solution development a technique for order preference by similarity to ideal solution (TOPSIS) is applied, using TOPSIS method in multi-attribute decision making (MADM) application. This is a classical multi-criteria decision making method, which was first proposed in 1981 (Dace et al., 2013). TOPSIS is based on the concept that the best alternative should be as close as possible to the ideal solution, as given results allows to select the best of a finite number of alternatives (Dace et al., 2013). Results of multi-criteria analysis are presented in part 3.7.

To carry out the method, decision matrix is constructed where *m* (row dimension) are fuel scenario alternatives (scenarios A-C) and *n* (column dimension) are evaluation criteria.

Selected evaluation criteria include: LCA results for each scenario, amount of produced ash estimated by theoretical calculations, calculated air emissions, which are converted using corresponding equivalents and economical costs. Economical costs are selected of produced respective SRF cost in market and usually applied waste treatment cost, for the waste type used in scenario developing. Selected criteria are presented in Table 2.12.

Table 2.12. Criteria used in decision matrix

Criteria Nr.	1	2	3	4	5	6	7	8
Criteria	LCA result, mPt	Ash, kg	CO_2 equivalent, kg	Acidifying potential equivalent, kg	TOFP[1] equivalent, kg	Particulate formation equivalent, kg	Produced fuel cost, Euro	Avoided waste treatment cost, Euro

Calculated air emissions are converted using suitable equivalents. Conversion data is given in Table 2.13 (de Leeuw, F.A.A.M., 2002). Using converted units it is possible to sum up values of the emissions equivalents of same environmental issue and to compare the

[1]Tropospheric Ozone Forming Potentials

scenarios to each other in a simplified way. Calculation of converted emissions is presented in Appendix 2.

Economical criteria, "Produced fuel cost" contents the price of such produced fuel in market, "Avoided waste treatment cost" is a cost of waste treatment, which is usually applied or the price is given by waste treatment center. For ELT it is treatment cost, supplied by region's waste management center, MSW – landfill gate fee, sludge – treatment cost estimated in the ENERCOM project.

Corresponding to selected criteria and results for each criterion given by scenarios A, B and C, a decision matrix is created in table 2.14.

Table 2.13. Conversion to equivalents data

Pollutant	Issue	Conversion	Units
CO_2	Global warming potential	1.0	kg CO_2 equivalent
NO_x	Acidifying potential	0.022	kg Acidifying potential equivalent
SO_2	Acidifying potential	0.031	kg Acidifying potential equivalent
CO	TOFP	0.110	kg TOFP equivalent
NO_x	TOFP	1.220	kg TOFP equivalent
SO_2	Particulate formation PM10	0.540	kg Particulate formation equivalent
NO_x	Particulate formation PM10	0.880	kg Particulate formation equivalent

An exception is applied to CO_2 equivalent results for scenario D. Selected SRF is produced from renewable sources, and renewable energy sources are accepted as "climate neutral" fuel (Kliopova and Makarskienė, 2015). Therefore, CO_2 emissions are zero.

Table 2.14. Decision matrix

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A	1.460	1.193	23.565	2.197	124.592	88.401	5.426	8.720
B	46.741	14.070	47.574	2.178	124.802	88.074	2.740	6.291
C	31.000	20.490	0.00	2.234	124.547	89.046	2.283	11.822

Where m (row dimensions) are fuel scenario alternatives and n (column dimensions) are evaluation criteria.

The first step of the applied TOPSIS technique, is to construct the normalize decision matrix, where various criteria dimensions are transformed into non-dimensional criteria, what allows comparison across the criteria. To determine normalized decision matrix Eq. 2.12 is applied.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{2.12}$$

Second step is to construct the weighted normalized decision matrix. In order to do so, each column is multiplied by its weight w_j, to get v_{ij}.

Weight for each criterion is given by the importance or dangers to the environment, weight are presented in table 2.15. LCA result has the biggest weight, as it includes waste material transformation to fuel stage, where energy and transportation is included. Amount of produced ash is desired to be as less as possible, but this criterion has the lowest weight in the analysis. CO_2 equivalent is taken as a slightly bigger weight than the rest, as it has global warming potential. Remaining criteria have the same weight as they are taken to be the same importance to the evaluation.

Table 2.15. Weight for each criterion

Criteria Nr.	1	2	3	4	5	6	7	8
Criteria	LCA result, mPt	Ash, kg	CO_2 equivalent, kg	Acidifying potential equivalent, kg	TOFP equivalent, kg	Particulate formation equivalent, kg	Produced fuel cost, Euro	Avoided waste treatment cost, Euro
Weight	0,3	0,05	0,15	0,1	0,1	0,1	0,1	0,1

In step 3, after weighted normalized decision matrix is completed, ideal and negative-ideal solutions are determined.

First of all ideal solution A^+ for each criteria is determined. In selected case it is ideal when criteria values related with environmental issues are minimal, as well minimal produced fuel cost. And avoided waste treatment cost is maximal, what would give the biggest benefit, by avoiding this cost.

Secondly, negative-ideal solution A^- is found. In this case it is the opposite to ideal solution: criteria related with environmental issues and produced fuel cost are maximal, waste treatment cost is minimal.

In step 4, separation measures from the solutions are calculated. In order to do so, separation from ideal solution S_i^+ has to be calculated for each row *j*, using Eq. (2.13). Separation from negative-ideal solution S_i^- is calculated analogical using the same formula.

$$S_i^* = \left[\sum (v_j^* - v_{ij})^2\right]^{1/2} \tag{2.13}$$

After determination of separation values, in step 5, relative closeness to the ideal solution is calculated, using the following formula 2.14.

$$c_i^* = \frac{S_i^-}{(S_i^+ + S_i^-)} \tag{2.14}$$

While:
$0 < c_i^+ < 1$,
$c_i^* = 1$ if $A_i = A^+$,
$c_i^* = 0$ if $A_i = A^-$.

Preference order is ranked by results of relative closeness to the ideal solution. Selected energy recovery scenarios are ranked by preference according to the descending order of c_i^*.

According to the ranking results selected fuels mixture ratio for scenario D is calculated and environmental impact of the scenario D is estimated and compared with the main scenarios A, B and C.

In scenario D, part of energy recovered for a functional unit – 1 GJ, energy recovery ratio ER_i is calculated using Eq. (2.15).

$$ER_i = \frac{c_i \times 100\%}{\sum c_i} \tag{2.15}$$

By the estimated fuel mix composition additional LCA scenario D is developed, using data from the basic scenarios A, B and C. In this scenario to generate 1 GJ of fuel input all previously estimated fuels are used, respectively to the fuel mix composition. According to amount of recovered energy by each fuel, mass of the fuel is calculated, by dividing it from LHV and final SRF mixture ratio composition is estimated in weight %.

The mixed fuel characteristics are calculated in respect of the composition part of each fuel. Generated environmental impact by 1 GJ fuel input production using fuel mix is allocated by the composition of each fuels and compared with basic scenarios, using the same criteria applied in multi-criteria analysis. Inventory data for developing scenario D and results are presented in part 3.8.

3. RESULTS AND DISCUSSION

3.1. Results from LCA method: Scenario A

The create gate-to-gate life cycle, SimaPro 8 software was used. Network of the scenario A is presented in Fig. 3.1.

To produce 1 GJ of heat energy, the main part impact is generated by transportation consisting of transportation from waste tires collection points to shredding facility and from shredding facility to incineration plant. Transportation of end-of-life tires is 0.317 mPt and shredded tire rubber is 0.468 mPt, what together gives 0.785 mPt value.

Remaining part of impact 0.667 mPt is generated during pre-treatment, which is carried out in tire shredding facility and mainly impacted by the use of electricity. During shredding produced scrap metal is recycled, giving a positive environmental impact for the process.

Total environmental impact of the scenario A for a functional unit is 1.45 mPt.

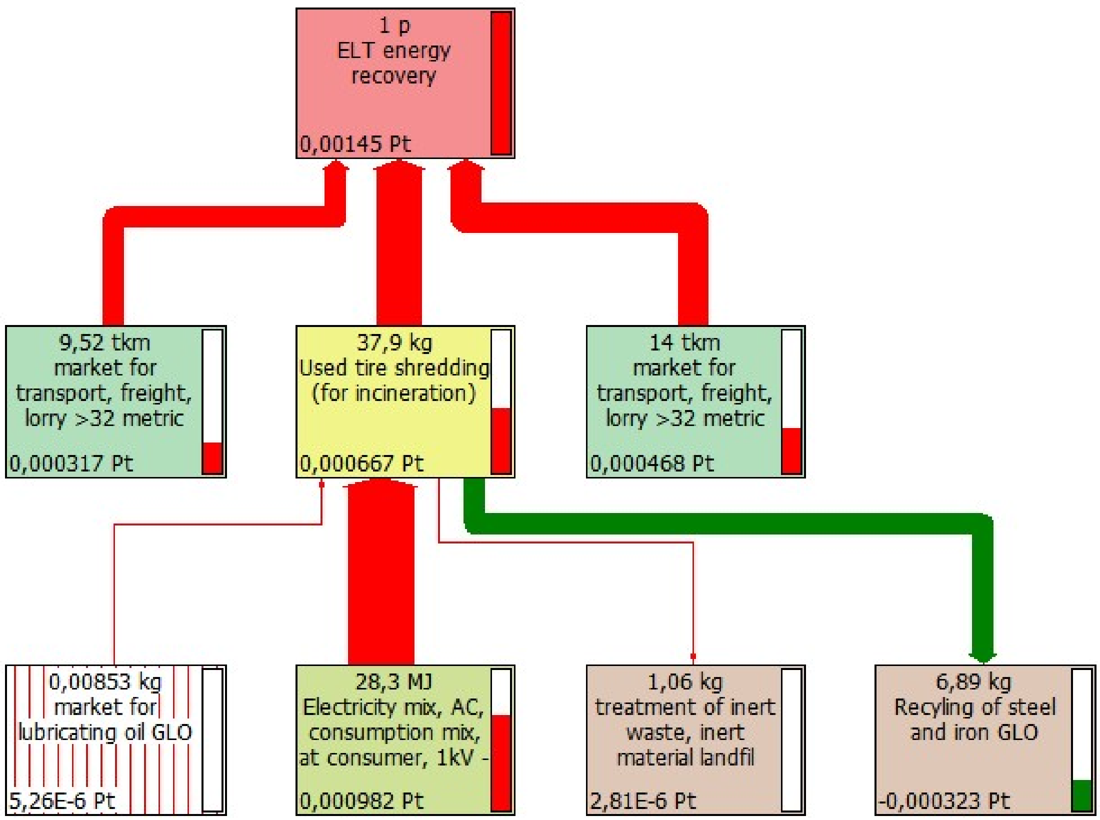


Fig.3.1. Network of scenario A

Generated impact for all selected impact categories for scenario A is presented in Fig. 3.2.

Used tire shredding process gives positive impact for such categories: Carcinogens 94.7% of all positive impact for category, Non-carcinogens 100%, Respiratory organics 20.8%, Aquatic acidification 16.3% and Aquatic eutrophication 17.7%. This positive impact values (in the program presented as negative) are because of scrap metal recycling and it reduces overall generated environmental impact.

The main affected categories by shredding process are: Ionizing radiation 93.3%, Ozone layer depletion 92.6% and Mineral extraction 98.6%. Shredding process creates environmental impact for other categories, what is visible in the chart.

Transportation mostly affects such categories as Respiratory organics100%, Aquatic acidification 100% and Aquatic eutrophication100%.

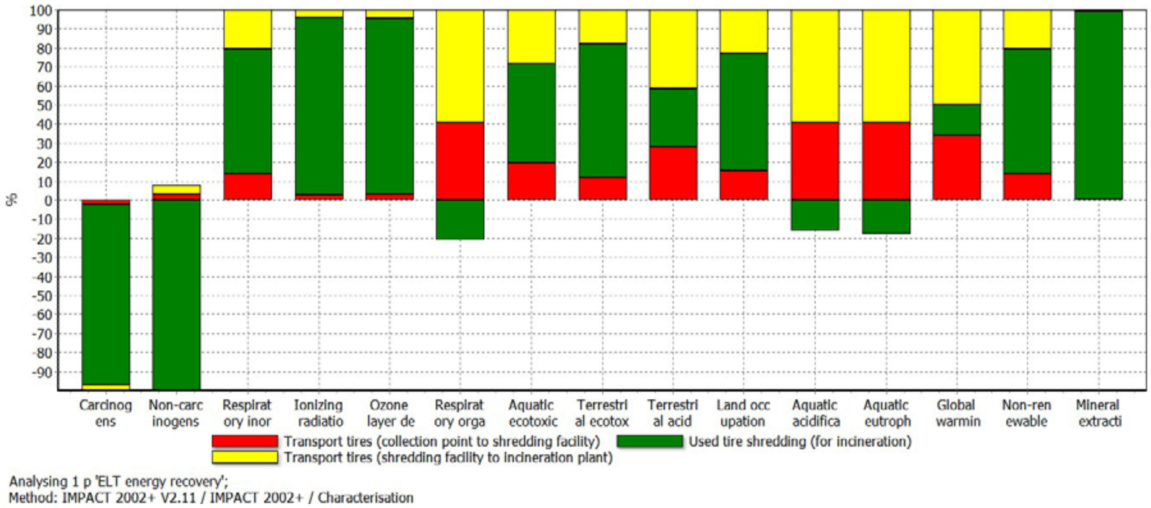


Fig.3.2. Impact categories of scenario A

In the following Fig. 3.3 and Fig. 3.4 damage assessment of the scenario is shown. From the charts can see that positive impact is created only on human health category, by used tire shredding process, which is equal to 0.374 mPt. Environmental impact created on ecosystem quality, climate change and resources is brought by all processes. Total impact for ecosystem quality reaches value of 0.323 mPt. Impact for climate change category is 0.320 mPt, resources category gives the highest part for total impact, which is equal to 1.006 mPt. Electricity consumption for shredding is the main reason of high affect to resources.

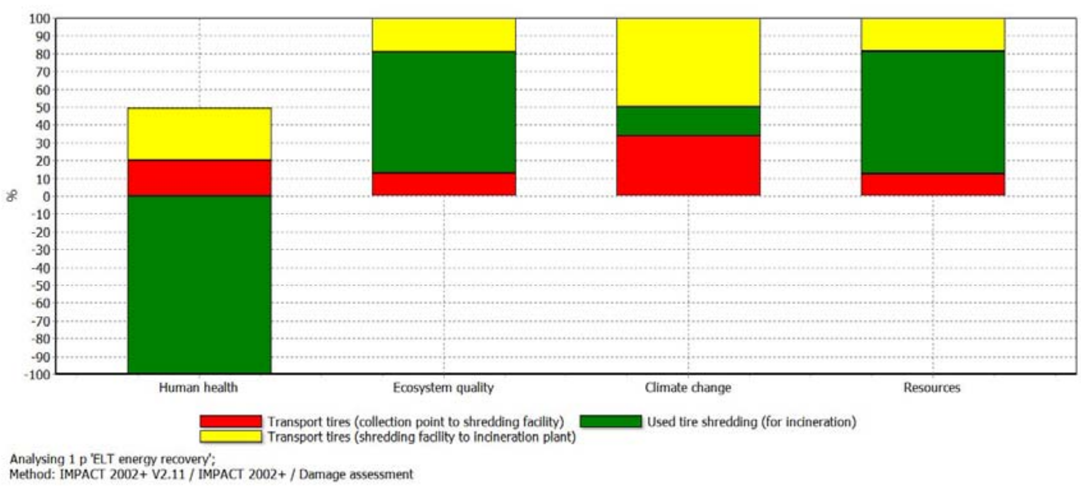


Fig.3.3. Damage assessment of scenario A

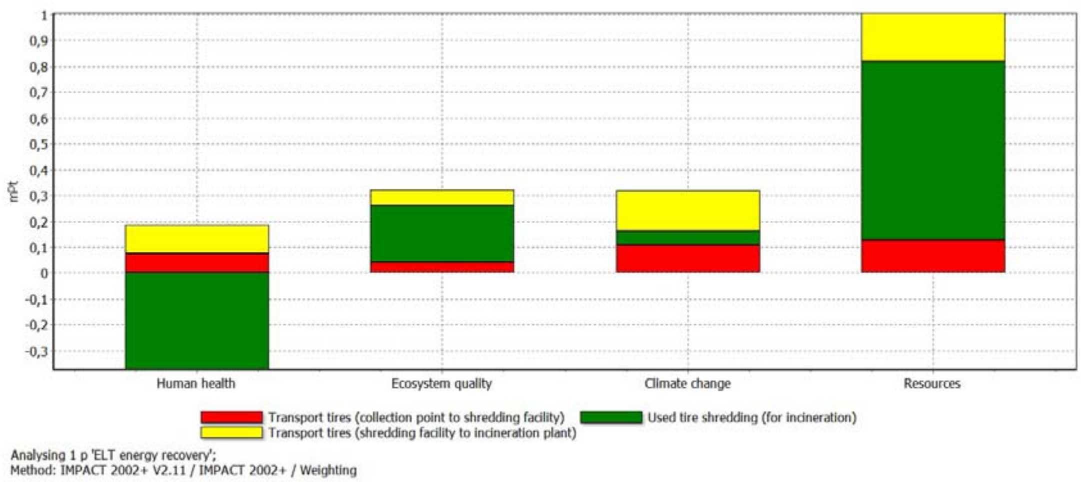


Fig.3.4. Damage assessment results after normalization and weighting for scenario A

3.2. Results from LCA method: Scenario B

Network for energy recovery from SRF produced from municipal solid waste is presented in Fig. 3.2. In this scenario the main environmental impact is given by MSW treatment to produce SRF. This is due to high electric energy consumption for waste sorting and processing. Positive environmental impact as well is created as recyclables materials are generated.

Transportation creates relatively small part of total environmental impact. MSW treatment process creates largest part of impact.

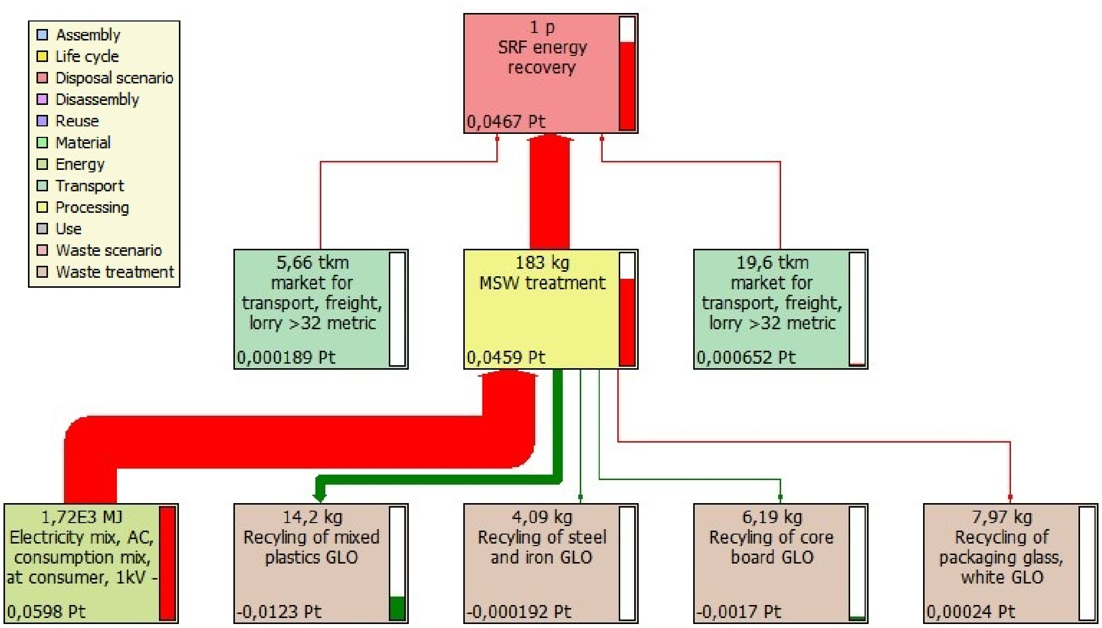


Fig.3.5. Network of scenario B

Impact on mid-point categories is presented in Fig. 3.6 and on end point damage categories in Fig. 3.7. A large positive impact is created for ecosystems quality, by MSW treatment process, because during process recyclable materials are sorted and given for recycling.

However ecosystem quality is highly affected by transportation, due to emissions from mobile sources.

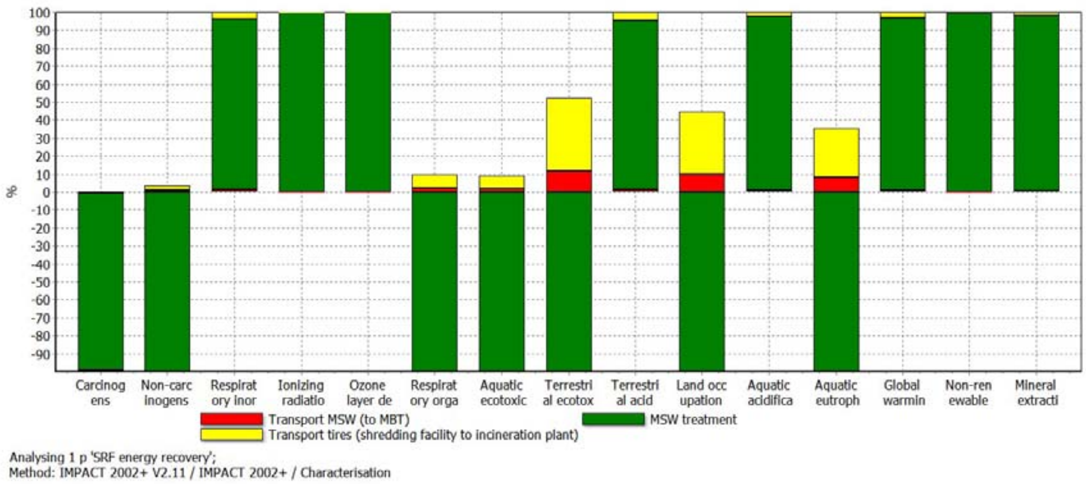


Fig.3.6. Impact categories of scenario B

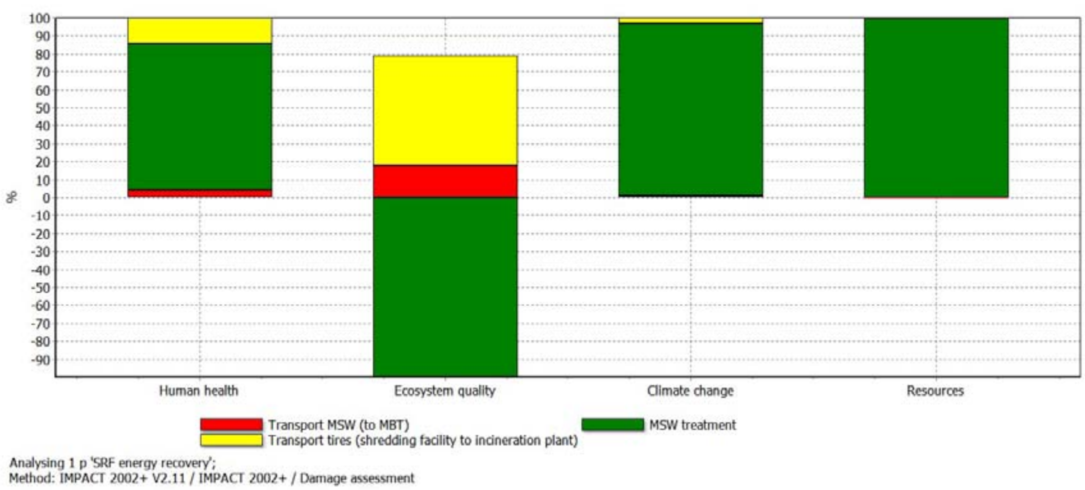


Fig.3.7. Damage assessment of scenario B

Fig. 3.8 represents the results after normalization and weighting process. From the chart we can see that by the scenario C the most impacted category is resources, where whole impact is brought by MSW treatment process. Climate change, human health and ecosystem quality are affected slightly.

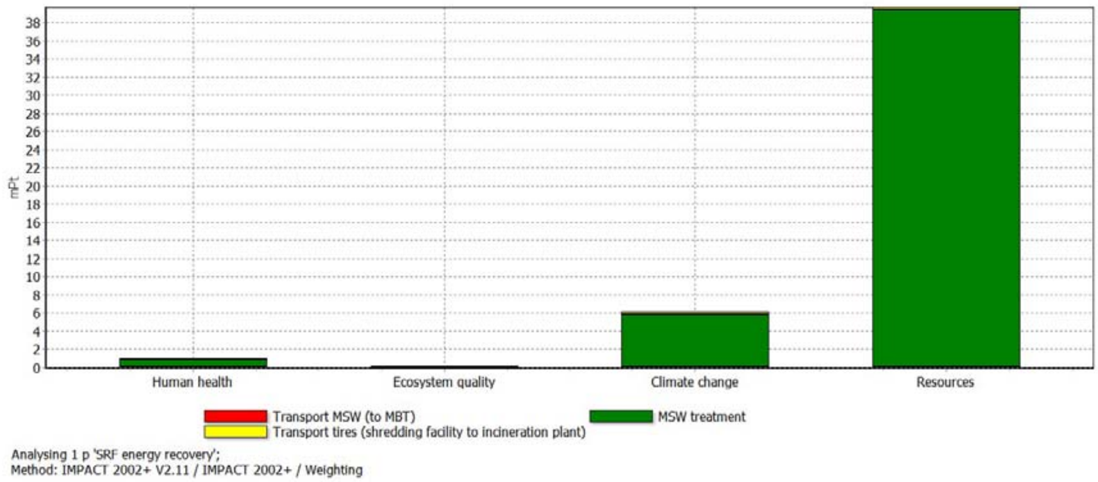


Fig.3.8. Damage results after normalization and weighting for scenario B

3.3. Results from LCA method: Scenario C

Network and environmental impact results for scenario C is given in Fig.3.10. Total environmental impact generated to recover 1 GJ of heat energy gives 31.0 mPt.

Most of the impact 22.3 mPt is created by SRF dewatering and pelleting process, by the use of electricity for processing.

Biomass transportation to pre-composting place has impact of 8.8 mPt, while transportation of SRF to incineration plant has only 0.08 mPt of impact. The difference is due to high mass difference in each transportation input; as well it might be affected by different environmental impact estimation of these transportation inputs.

SRF composting has only 0.17 mPt impact and do not carry a significant environmental load.

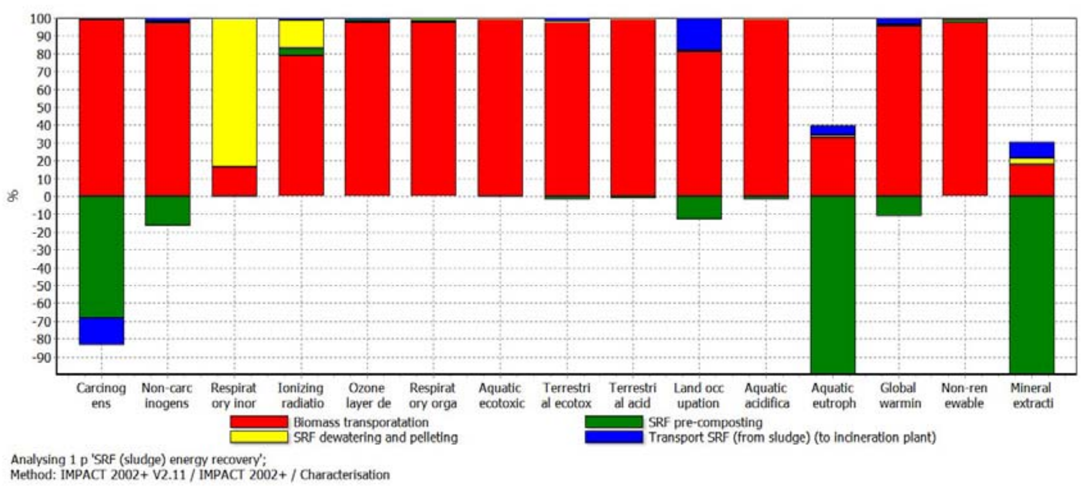


Fig.3.9. Impact categories of scenario C

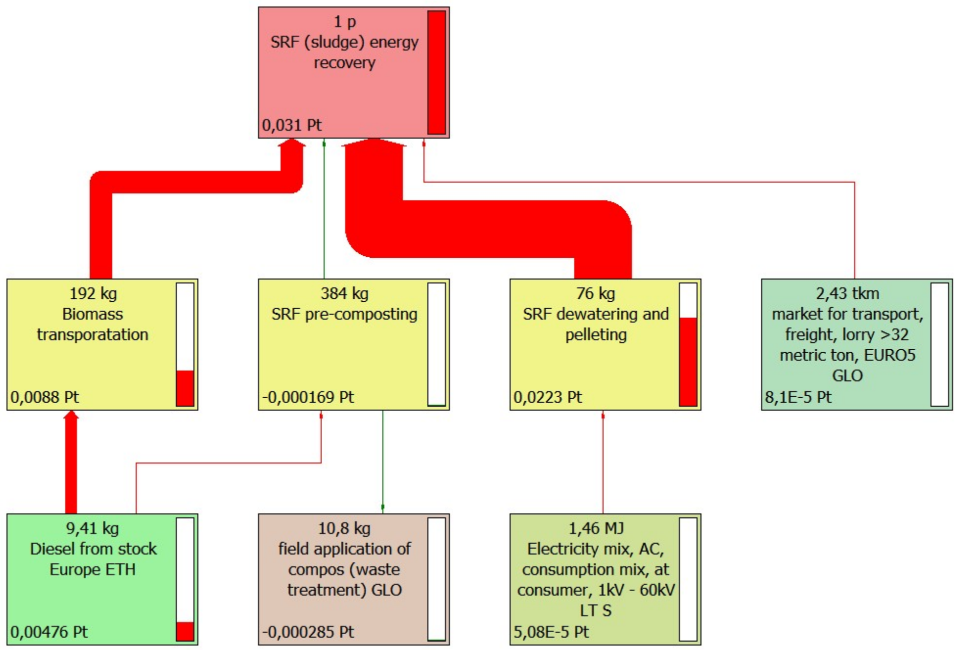


Fig.3.10. Network of scenario C

Damage assessment for all selected impact categories is given in Fig. 3.9. Positive impact is created by SRF pre-composting process, as during it, compost is generated and used further. Clearly visible that biomass transportation creates the largest part of impacts for most of categories.

SRF production process creates impact for Respiratory organics, as particulate matter is emitted during SRF pelleting.

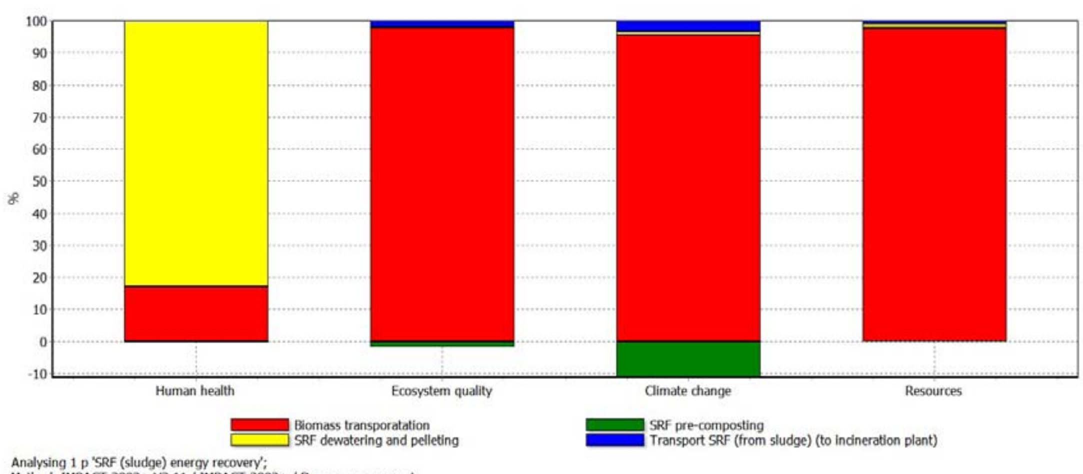


Fig.3.11. Damage assessment of scenario C

The most damaged category in this scenario is human health, for which created environmental impact is 26.6 mPt, what is close to whole impact per functional unit. The impact on category is created from electricity use to SRF dewatering and pelleting and by diesel consumption for biomass transportation.

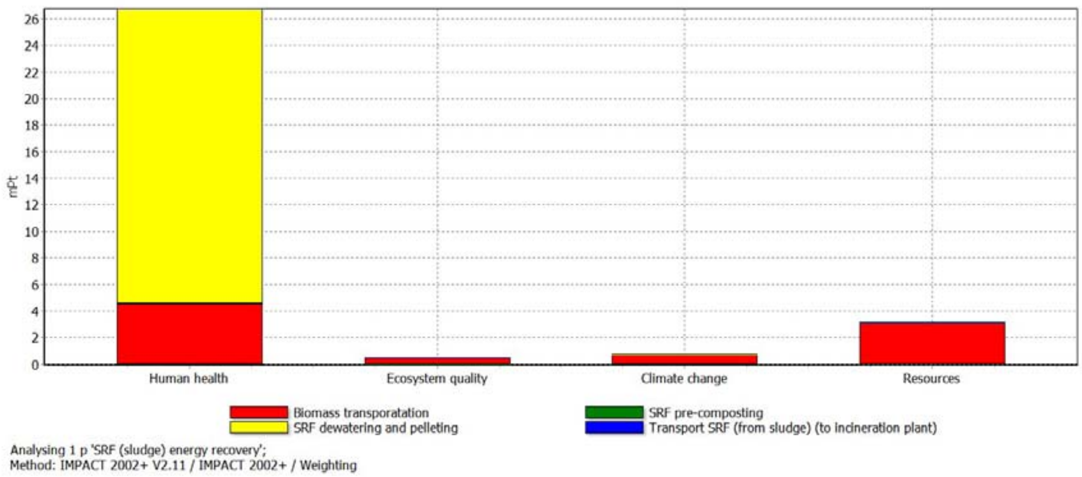


Fig.3.12. Damage results after normalization and weighting for scenario C

3.4. Comparison of the LCA results

LCA results from conducted scenarios A, B and C are compared with each other in the following figures 3.13 and 3.14.

Fig. 3.13 represents single score results comparison. In figure big difference between energy recovery scenario from ELT and other scenarios is clearly visible, as scenario A has score of only 1.45 mPt. The highest impact is from scenario B, which reaches 46.7 mPt. Scenario B and scenario C has a difference of 15.6 mPt, which reflects in the graph. Energy recovery scenario from SRF from MSW creates large resources depletion, due to high electricity consumption, energy recovery from SRF out of sludge, creates high impact on human health, due to diesel consumptions for transportation.

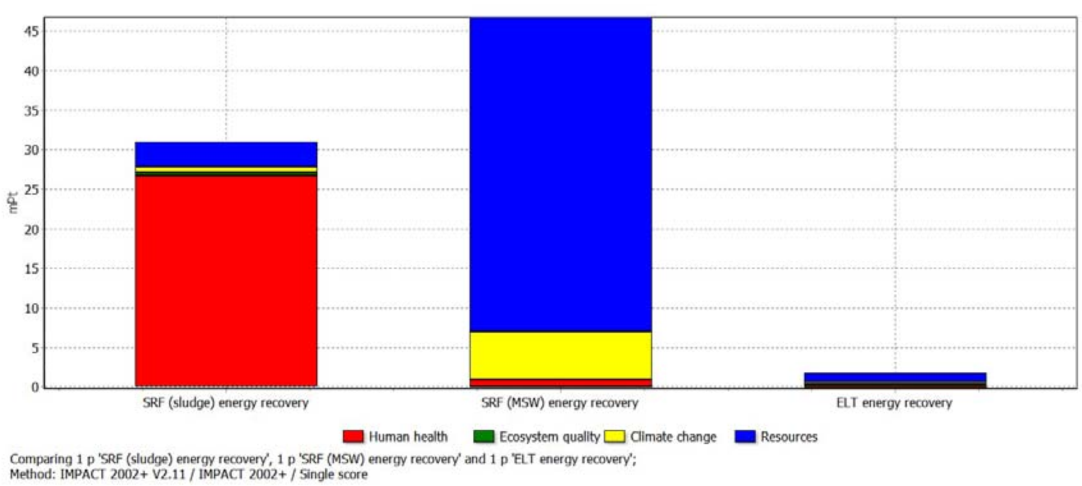


Fig.3.13. Single score results comparison

Fig. 3.14 shows weighting results comparison for the scenarios. As noticed from scenario C results, that it has a strong affect to human health, it reflects as well in the comparison. As well on resources highest impact is created by energy recovery from SRF from MSW. From chart it possible to say that selected energy recovery scenarios do not affect significantly ecosystem quality and climate change.

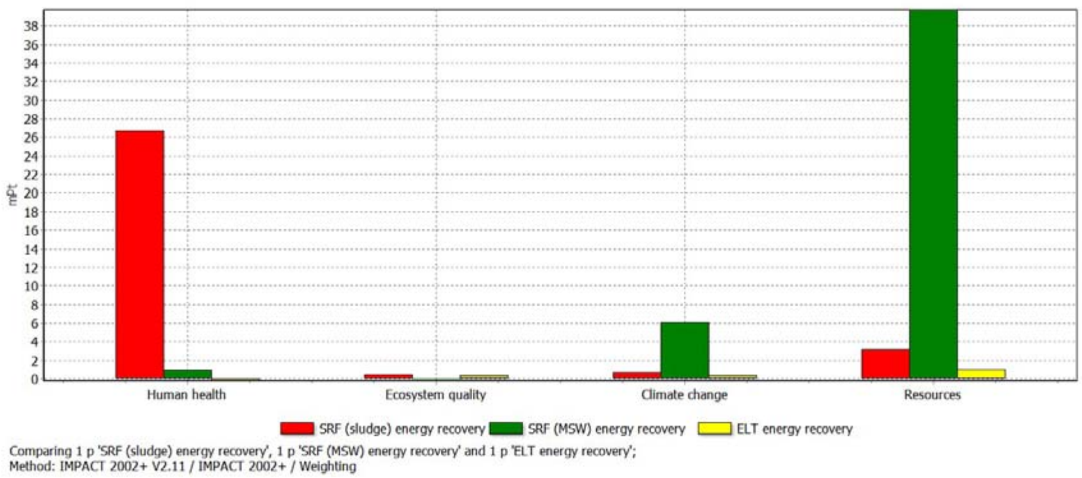


Fig.3.14. Weighting results comparison

3.5. Sensitivity analysis

Carrying out the sensitivity analysis, selected parameters were increased for each scenario and the change for final LCA single score result were observed. Sensitivity analysis presented for scenarios A, B and C in Tables 3.1, 3.2 and 3.3 respectively.

After carrying out the analysis, a change of life cycle assessment result and result increase in percent is given in the tables and showed in graph (Fig. 3.15) for each scenario separately. LCA result for scenario A was 1.45 mPt. Scenario B total LCA result was 46.7 mPt and result of scenario D was 31.0 mPt.

Fig. 3.15 shows that in scenario A and B, LCA results are most sensitive to electricity input, however only for scenario B, it is considered as sensitive, as it the LCA result increased by 12.8%, what is >10%. As well, from figure can see that in scenario C, LCA result is sensitive only to biomass transportation, as it generates large part of total environmental impact.

Table 3.1. Sensitivity analysis for scenario A

Nr.	**Input**	LCA result, mPt	Result increase, %
1.	Transport tires (collection points to shredding facility – 251 km)	1.48	2.1
2.	Transport tires (shredding facility to incineration plant – 370 km)	1.50	3.4
3.	Electricity mix	1.55	6.9

Changes observed in scenario C, shows that result is slightly sensitive to biomass transportation increase. Energy use increase had no change for the overall LCA result.

Table 3.2. Sensitivity analysis for scenario B

Nr.	**Input**	LCA result, mPt	Result increase, %
1.	Transportation (collection to shredding fac. – 31 km)	46.7	<0.01%
2.	Transportation(shredding fac. to incin. plant – 300 km)	46.8	0.2
3.	Electricity mix	52.7	12.8

Sensitivity analysis results show that overall result changes significantly only in scenario B, due to electricity consumption. This is because of high amount of electricity used in the scenario and environmental impact created by it, is an important overall impact component.

Table 3.3. Sensitivity analysis for scenario C

Nr.	**Input**	LCA result, mPt	Result increase, %
1.	Transportation of biomass (diesel consumption)	31.8	2.6
2.	Transportation (SRF production facility to incineration plant – 34 km)	31.0	<0.01%
3.	Diesel for Residues milling, composting,	31.0	<0.01%
4.	Electricity mix	31.0	<0.01%

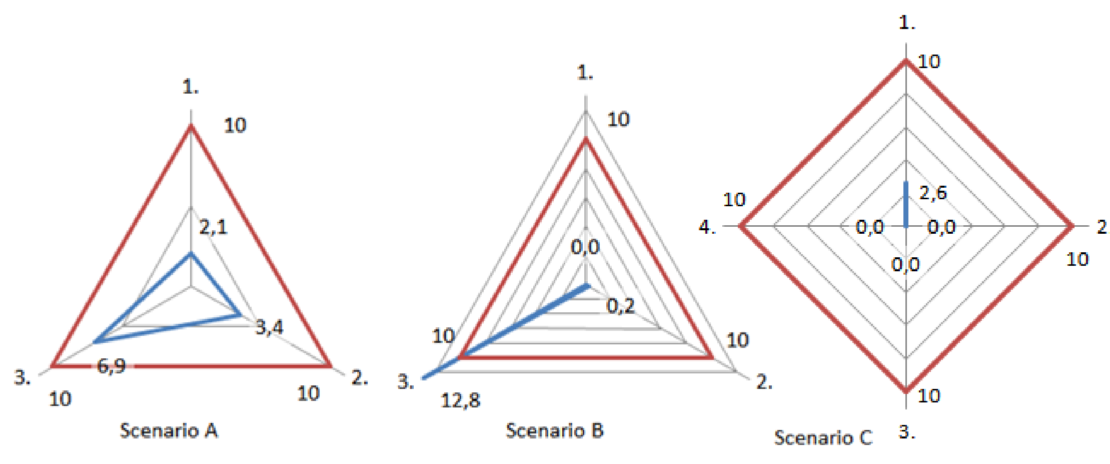


Fig.3.15. Sensitivity analysis results

3.6. Theoretical calculations method results

Using theoretical calculations method the amount of produced ash and expected incineration emissions were estimated, the results are presented in Table 3.4.

Table 3.4. Theoretical calculations results per functional unit (kg/FU)

	Ash	SO_2	O_2	CO	CO_2	N_2	NO_x
Scenario A	1.193	0.742	31.194	23.565	44.013	359.416	100.000
Scenario B	14.070	0.137	30.389	25.472	47.574	350.305	100.000
Scenario C	20.490	1.937	31.402	23.150	42.238	363.590	100.000

From the table we can see that amount of produced ash by scenario A is significantly lower, compared to scenarios B and C. This is due to low ash content in material about 4%, as well the amount of tires rubber used is low, because of high calorific value. Ash amount for scenarios B and C is more similar, as ash content is 22% and 27% respectively. However, larger amount of material and higher ash content determines larger ash amount for scenario C.

Comparing expected emissions, the biggest difference is for SO_2 emissions, which in scenario B is very low only 0.14 kg, while for scenario C it reaches 1.9 kg of SO_2. The amount of SO_2 depends only on sulphur content in the fuel. Results of O_2, CO, CO_2 and N_2 are very similar for all scenarios. NO_x emissions for all scenarios are the same, as it is estimated by the amount of heat produced. Important thing to be noted, that emissions from scenario C are emissions from renewable energy sources and accepted as "climate neutral" (Kliopova and Makarskienė, 2015).

3.7. Results of multi-criteria analysis of scenarios preference

Applied technique for order preference by similarity to ideal solution (TOPSIS) is carried out in 5 steps.

Step 1, normalized decision matrix r_{ij} is made (Table 3.5).

Table 3.5. Normalized decision matrix

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A	0,026	0,048	0,444	0,576	0,577	0,577	0,836	0,546
B	0,833	0,565	0,896	0,571	0,578	0,575	0,422	0,394
C	0,553	0,823	0,000	0,585	0,577	0,581	0,352	0,740

Step 2, weighted normalized decision matrix v_{ij} is calculated (Table 3.6).

Table 3.6. Weighted normalized decision matrix

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A	0,008	0,002	0,067	0,058	0,058	0,058	0,084	0,055
B	0,250	0,028	0,134	0,057	0,058	0,057	0,042	0,039
C	0,166	0,041	0,000	0,059	0,058	0,058	0,035	0,074

In step 3, ideal solution A^+ is determined for each criterion.
A^+={0.008, 0.002, 0.052, 0.000, 0.057, 0.058, 0.035, 0.074}
As well negative-ideal solution A^- is determined for each criterion.
A^-={0.250, 0.041, 0.134, 0.059, 0.058, 0.058, 0.084, 0.039}

In step 4, separations from solutions are estimated. Separation from ideal solution S_i^+ and separation from negative-ideal solution S_i^- are calculated for each row *j*. Results are given in table 3.7.

Table 3.7. Separations from ideal solution

	S_i^+	S_i^-
Scenario A	0,085	0,255
Scenario B	0,280	0,043
Scenario C	0,163	0,169

In step 5, relative closeness to the ideal solution c_i^* for each scenario is calculated using corresponding formula. Calculation results are given in Table 3.8.

Selected energy recovery scenarios are ranked by preference according to the descending order of c_i^* and the ranking is presented in Table 3.8.

Table 3.8. Scenarios ranking results

	c_i^*	Preference
Scenario A	0,751	Best
Scenario B	0,134	Worst
Scenario C	0,510	

Preference ranking results gives the conclusion that energy recovery scenario A, from end-of-life tires is the most preferable having a ranking result 0.751, which is closest to 1. Scenario C (energy recovery from SRF produced from pre-composted municipal waste water sludge and biomass) is the second most preferable with result 0.510, although having small disparity from most preferable result. Scenario B (energy recovery from SRF produced from MSW) is the least preferable with significantly lowest result 0.134.

3.8. Inventory data and results of scenario D

Using the given ranking results, energy recovery ratio ER_i by each fuel scenario, in scenario D is calculated and results are presented in table 3.9. According to amount of recovered energy by each fuel, mass of the fuel is calculated and final SRF mixture ratio is estimated.

Table 3.9. Estimated feasible fuel mix composition

Fuel	ER_i, %	Energy recovered, MJ	LHV, MJ/kg	Fuel mass, kg	SRF mixture ratio, %
End-of-life tires	53.828	538.278	33.353	16.139	32.151
SRF from MSW	9.600	96.002	15.327	6.264	12.478
SRF from sewage sludge and biomass	36.572	365.720	13.158	27.795	55.371

Inventory analysis is allocated regarding to the inventory analysis of scenarios for single fuel energy recovery. Inventory analysis for scenario D is presented in table 3.12.

Mixed SRF fuel characteristics are estimated respectively by the part of each fuel and composition of it, characteristics are given in Table 3.10.

Table 3.10. Mixed fuel characteristics, scenario D

Fuel	Composition (wt. %)							HHV	LHV
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	Moisture	MJ/kg	MJ/kg
MIX	47.913	5.398	16.405	1.395	1.134	18.899	8.856	21.358	19.922

Incineration emissions and generated amount of ash were estimated using theoretical calculations method, results given in Table 3.11.

Table 3.11. Theoretical calculations results for scenario D per functional unit (kg/FU)

	Ash	SO_2	O_2	CO	CO_2	N_2	NO_x
Scenario D	9.486	1.121	31.193	23.868	44.578	360.067	100.000

Table 3.12. Inventory analysis for scenario D

Material	Amount	Unit
Input		
End-of-life tires	20.099	kg/FU
Municipal solid waste	17.535	kg/FU
Sewage sludge	70.302	kg/FU
Biomass waste	70.302	kg/FU
Transportation	Amount	unit
Transport tires (collection points to shredding facility)	5.045	tkm
Transport tires (shredding facility to incineration plant)	7.437	tkm
Transportation of MSW (collection points to MBT)	0.544	tkm
Transportation of SRF from MSW (MBT to incineration plant)	1.879	tkm
Transportation of biomass (diesel consumption)	3.374	kg/FU
Transportation of SRF from sludge and biomass (production facility to incineration plant)	0.889	tkm
Processing	Amount	Unit
Used tire shredding (for incineration)	20.099	kg/FU
Input		
Lubricating oil	0.0045	kg/FU
Electricity mix	4.165	kWh/FU
Output (waste to treatment)		
Inert waste	0.563	kg/FU
Scrap metal (for recycling)	3.649	kg/FU
MSW treatment in MBT	17.535	kg/FU
Input		
Electricity mix	45.933	kWh/FU
Output (waste to treatment)		
Paper and cardboard (recycling)	0.594	kg/FU
Plastic (recycling)	1.365	kg/FU
Glass (recycling)	0.765	kg/FU
Metals (recycling)	0.393	kg/FU
Other waste not suitable for treatment (landfilling)	0.526	kg/FU
SRF pre-composting	140.604	kg/FU
Input		
Diesel for Residues milling, composting,	0.068	kg/FU
Water	0.014	m^3/FU
Industrial oil	0.0013	kg/FU
Output		
Compost for further composting	32.029	kg/FU
Waste water	0.052	m^3/FU
Dewatering and pelleting of SRF	27.793	kg/FU
Input		
Electricity mix	0.156	kWh/FU
Water	0.014	m^3/FU
Output		
Waste water	0.014	m^3/FU
PM emissions from pelleting process	0.551	kg/FU

Using inventory data, gate-to-gate life cycle for scenario D was created, the network is shown in Fig. 3.15. The network includes processes used for previous scenarios modelling. The general impact, created by 1 GJ fuel input production using ELT and SRF from MSW and sludge, is 16.6 mPt. The given result in compare with previous scenarios is not the lowest, as the lowest still remains for scenario A – 1.460 mPt. Although, the result is lower than scenarios B and C results, which are 46.741 mPt and 31.0 mPt.

The biggest impact in the scenario is given from SRF dewatering and pelleting, due to electric energy used for process. As well SRF from sludge forms more than half of all fuel mixture mass. Another large part of impact is generated by MSW treatment, even SRF from MSW is the lowest part of fuel mixture. Biomass transportation has slightly lower impact than MSW treatment. Mass of biomass for SRF production is high; therefore the impact given is such. Remaining processes, such as ELT shredding, SRF pre-composting, together with materials transportations generate small environmental impact. Some of the processes are not visible in the network, as processes creating very small impact are cut-off. However, impact by cut-off processes is included in the final result.

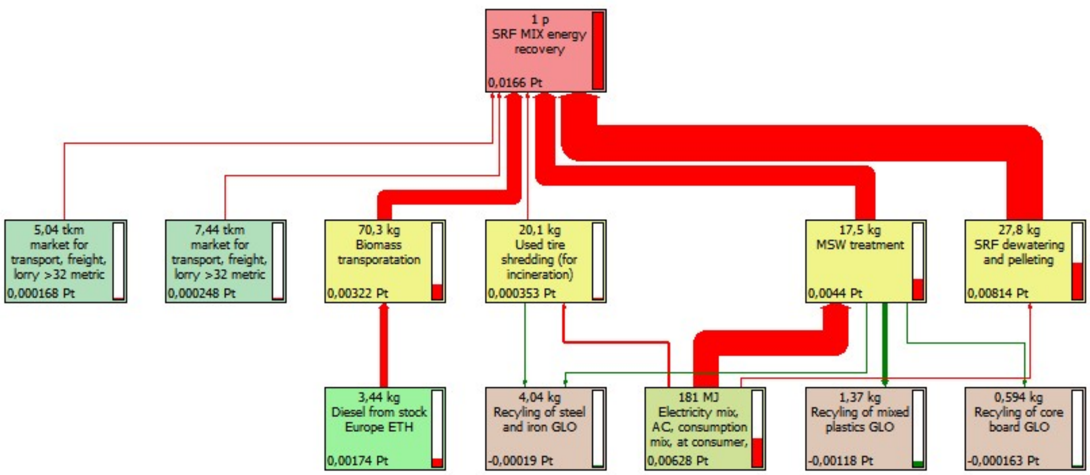


Fig.3.16. Network of scenario D

Fig. 3.16 represents normalized and weighted environmental damage results for the four main damage criteria. From the figure it is visible that largest impact is created to resources and human health.

Resources depletion is created mostly by MSW treatment, due to high electricity consumption and biomass transportation, due to use of diesel.

Climate change as well is mostly impacted by MSW treatment, due to electricity consumption.

Human health is affected by SRF dewatering process and biomass transportation. For both processes, one of the inputs was diesel, which use has a large negative impact to human health.

Ecosystem quality is affected the lowest in this scenario, together by all the included processes.

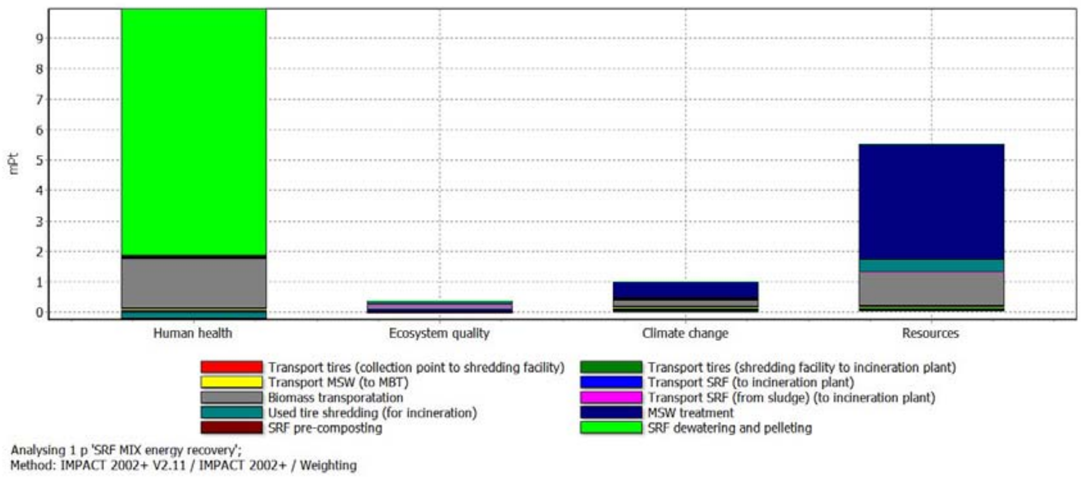


Fig.3.17. Damage results after normalization and weighting for scenario D

Comparison of the developed scenario D and primary scenarios A, B and C results are presented in Fig. 3.18 and 3.19.

Fig. 3.18 proves energy recovery from SRF mixture (scenario D) has one of the lowest impacts, after energy recovery from end-of-life tires. In scenario D, 55% of the fuel in mixture is SRF from sludge, but due to other fuels in the composition, impact on human health created by SRF from sludge is reduced approximately 5 times. However because of SRF from MSW, scenario D has higher resources depletion, comparing scenarios A and C.

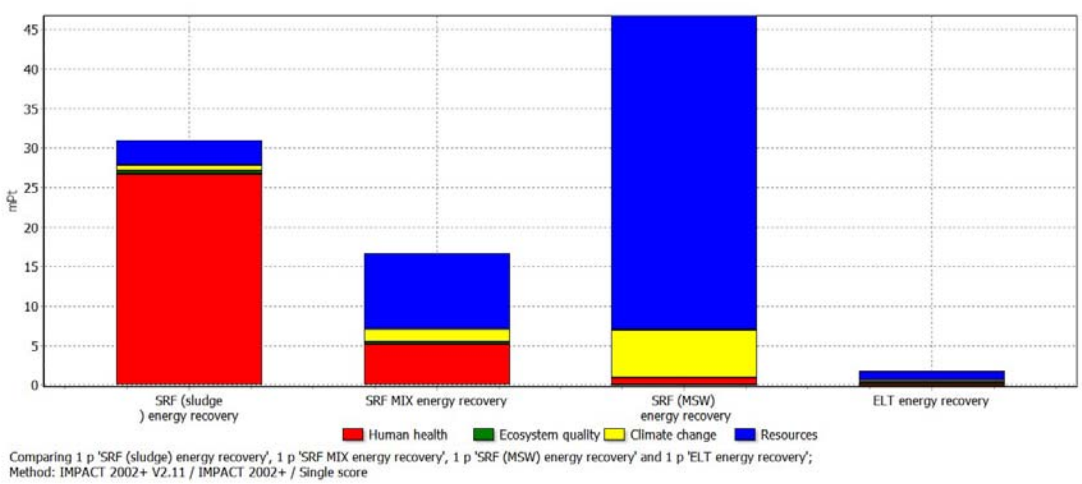


Fig.3.18. Scenarios A, B, C and D results comparison in single score

In Fig. 3.19 weighting results for all scenarios are presented. From figure can see comparison of environmental impact to each category by all scenarios. Developed scenario D (presented in green columns) has significantly lower impact to human health than scenario C and lower impact to resources than scenario B. Impact for ecosystem quality and climate change by developed scenario is similar to previous scenarios and very low.

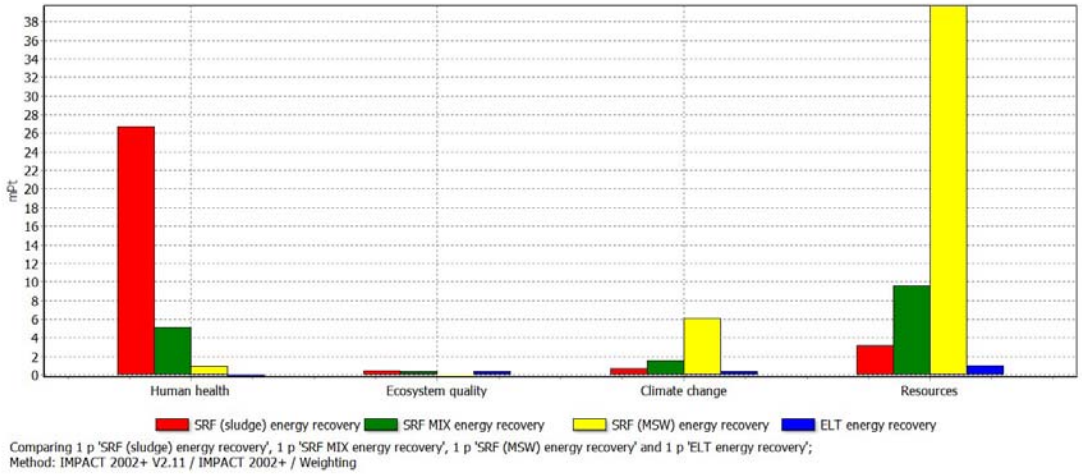


Fig.3.19. Scenarios A, B, C and D results comparison in weigting

For evaluation of created scenario D feasibility, TOPSIS method is applied again. All four scenarios are compared, by applying the same previously used criteria and criteria weighting. Created decision matrix is given in Table 3.13.

Table 3.13. Decision matrix with weighting

Weight	0,3	0,05	0,15	0,1	0,1	0,1	0,1	0,1
	LCA result, mPt	Ash, kg	CO_2 equivalent, kg	Acidifying potential equivalent, kg	TOFP equivalent, kg	Particulate formation equivalent, kg	Produced fuel cost in market, Euro	Waste treatment cost, Euro
Scenario A	1,460	1,193	23,565	2,197	124,592	88,401	5,426	8,720
Scenario B	46,741	14,070	47,574	2,178	124,802	88,074	2,740	6,291
Scenario C	31,000	20,490	0,000	2,234	124,547	89,046	2,283	11,822
Scenario D	16,600	7,132	44,578	2,209	124,625	88,605	3,957	4,932

Final results from the method gave scenarios preference ranking, which is as follows:

	c_i^*	Preference
Scenario A	0,779	Best
Scenario B	0,127	Worst
Scenario C	0,475	
Scenario D	0,542	2nd best

The given ranking shows that scenario D is 2nd most preferable, after the end-of-life tires scenario. Thus, mixing higher quality less-available fuel (ELT) with lower quality more-available fuel (MSW and sludge) should be applied whenever possible. Mixing three types of fuel would provide a higher utilization rate of MSW and sludge for producing fuel and recovering energy, rather than when used alone due to quality and economic reasons.

CONCLUSIONS AND RECOMMENDATIONS

This life cycle assessment study was aimed to compare energy recovery routes from end-of-life tires with other solid recovered fuels and to find the possible composition of mixed solid recovered fuel, containing all previously assessed fuels.

Carrying out the LCA studies on selected scenarios A, B and C the results showed that energy recovery from ELT (scenario A) has the lowest environmental impact. The main reason for such results is that tire rubber is containing almost 80% of carbon and is dry. These parameters influence calorific value of the fuel, which exceeds 30 MJ/kg. As compared to traditional solid fuels the lower calorific value of ELT is similar to the value of coal which is approximately 25 MJ/kg. Because of the calorific value, ELT has a high potential for energy recovery by replacing the traditional fuels or mixing it with other waste derived fuels that have lower calorific value, so as to increase the overall quality of the mixed fuel. Nevertheless, also MSW and sludge can be used for producing solid recovered fuels as their LHV equals 15.3 MJ/kg and 13.2 MJ/kg, respectively.

Theoretical calculations method gave results of specific emissions and ash content in the fuels assessed. Taking in mind that amount of fuel in scenario A is lower than of other fuels, emissions generated were not relatively lower in all the cases. Again this is due to high carbon content in the fuel. However, it is known that incineration of tires rubber creates a variety of other emissions, such as volatile organic compounds or metals, which were not estimated in the thesis and might affect the final results.

Considering the varying quality and environmental and economic aspects of the fuels assessed multi-criteria analysis was applied to estimate the most feasible type of fuel, as well as to create a fuel mixture. The multi-criteria analysis results created basis for development of additional scenario (scenario D) to be evaluated by LCA. The LCA results indicated that scenario D has impact of 16.6 mPt, what was lower than for energy recovery scenarios from SRF (scenarios B and C).

Finally, additional multi-criteria analysis of all four types of fuels (scenarios A-D), indicated that fuel mixture (scenario D) is more preferable than SRF produced from MSW or sludge (scenarios B and C) and only fuel from ELT (scenario A) has a slightly higher preference. It shows that the aim of the thesis is achieved and the mixed SRF scenario has a feasible composition and relatively low environmental impact, in comparison to other "primary" types of fuel.

To finalize the thesis main conclusions are as follows:

1. Energy recovery from end-of-life tires generates the lowest environmental impact, which is equal to 1.46 mPt, in compare with energy recovery from selected solid recovered fuels;
2. To recover 1 GJ of energy input it is needed to consume 30 kg of waste tires or 183 kg of municipal solid waste, or 192 kg of sewage sludge together with 192 kg biomass waste;
3. Using TOPSIS method for multi-criteria analysis, estimated most preferable energy recovery options is from end-of-life tires (scenario A), second preferable – energy recovery from SRF of sewage sludge and biomass (scenario C), least preferable – SRF made of MSW (scenario B);
4. Estimated feasible selected fuels mixing composition (applied in scenario D) is as follows: 32.1% of ELT rubber and 12.5% of SRF from MSW and 55.4% of SRF from sewage sludge with biomass waste;
5. To recover 1 GJ of input using selected fuels mixture, it is needed 20 kg of ELT, 18 kg of MSW and 70 kg of sewage sludge and biomass waste each;

6. Developed scenario D, showed good results in LCA and multi-criteria analysis in compare with the primary study scenarios. Even though, the result was not the best, still it has a benefit, as when SRF from MSW or waste water sludge is used for energy recovery, by avoiding disposal or other waste treatment.

In the next step it is recommended to expand the boundaries of processes used in the study. To get the full environmental impact the study boundaries should be extended by including incineration process into the LCA foreground system. This would allow to have a more accurate results of the impacts generated, as the same model would be applied for the impact given by emissions estimation. By including incineration process, all input and output flows have to be identified and estimated, such as energy use for incineration and energy and material use for flue gas treatment. Other types of waste fuels might be added and compared together with the selected ones, in order to evaluate their environmental impact and preference. The results given by this study might encourage the use of non-popular and underestimated waste derived fuels, by co-incinerating with other higher quality fuels.

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APPENDICES

Appendix 1

CO and CO_2 calculations and results for scenario A, B and C.

Scenario A						
LHV, kJ/kg	33353,5	33353,5	33353,5	33353,5	33353,5	33353,5
	Heat Loss due to Chemically Incomplete Combustion					
q3, %	0	0,2	0,4	0,6	0,8	1
q3, kJ/kg	0	66,707	133,414	200,121	266,828	333,535
CO density at normal conditions, kg/m3	1,249	1,249	1,249	1,249	1,249	1,249
LHV_{CO}, kJ/m3 CO	12648	12648	12648	12648	12648	12648
CO volume, m3 CO/kg fuel	0	0,00527	0,01055	0,01582	0,02110	0,02637
CO mass, kg CO/kg fuel	0	0,006589	0,013178	0,019767	0,026356	0,032945
CO mass, g CO/kg fuel	0,000	6,589	13,178	19,767	26,356	32,945
C in CO, kg C/kg fuel	0,000	0,003	0,006	0,008	0,011	0,014
C in fuel, kg C/kg fuel	0,79208	0,79208	0,79208	0,79208	0,79208	0,79208
C in CO2, kg C/kg fuel	0,792	0,789	0,786	0,784	0,781	0,778
CO2 in complete combustion, m3/kg	1,48117	1,48117	1,48117	1,48117	1,48117	1,48117
CO2 density at normal conditions, kg/m3	1,963	1,963	1,963	1,963	1,963	1,963
CO2 mass in complete combustion, kg CO2/kg fuel	2,9078	2,9078	2,9078	2,9078	2,9078	2,9078
C in CO2 in complete combustion, kg C/kg fuel	0,793	0,793	0,793	0,793	0,793	0,793
CO2 in uncomplete combustion, m3/kg	1,48120	1,476	1,471	1,465	1,460	1,455
CO2 density at normal conditions, kg/m3	1,963	1,963	1,963	1,963	1,963	1,963
CO2 mass in uncomplete combustion, kg CO2/kg fuel	2,9078	2,8975	2,8871	2,8767	2,8664	2,8560
C in CO2 in uncomplete combustion, kg C/kg fuel	0,793	0,790	0,787	0,785	0,782	0,779

Scenario B						
LHV, kJ/kg	15326,69	15326,69	15326,69	15326,69	15326,69	15326,69
	Heat Loss due to Chemically Incomplete Combustion					
q3, %	0	0,2	0,4	0,6	0,8	1
q3, kJ/kg	0	30,65338	61,30676	91,96014	122,6135	153,2669
CO density at normal conditions, kg/m3	1,249	1,249	1,249	1,249	1,249	1,249
LHV_{CO}, kJ/m3 CO	12648	12648	12648	12648	12648	12648
CO volume, m3 CO/kg fuel	0	0,002424	0,004847	0,007271	0,009694	0,012118
CO mass, kg CO/kg fuel	0	0,003028	0,006055	0,009083	0,012111	0,015139
CO mass, g CO/kg fuel	0,000	3,028	6,055	9,083	12,111	15,139
C in CO, kg C/kg fuel	0,000	0,001	0,003	0,004	0,005	0,006
C in fuel, kg C/kg fuel	0,393166	0,393166	0,393166	0,393166	0,393166	0,393166
C in CO2, kg C/kg fuel	0,393	0,392	0,391	0,389	0,388	0,387
CO2 in complete combustion, m3/kg	0,73522	0,73522	0,73522	0,73522	0,73522	0,73522
CO2 density at normal conditions, kg/m3	1,963	1,963	1,963	1,963	1,963	1,963
CO2 mass in complete combustion, kg CO2/kg fuel	1,4434	1,4434	1,4434	1,4434	1,4434	1,4434
C in CO2 in complete combustion, kg C/kg fuel	0,394	0,394	0,394	0,394	0,394	0,394
CO2 in uncomplete combustion, m3/kg	0,73522	0,733	0,730	0,728	0,726	0,723
CO2 density at normal conditions, kg/m3	1,963	1,963	1,963	1,963	1,963	1,963
CO2 mass in uncomplete combustion, kg CO2/kg fuel	1,4434	1,4386	1,4338	1,4291	1,4243	1,4195
C in CO2 in uncomplete combustion, kg C/kg fuel	0,394	0,392	0,391	0,390	0,388	0,387

Scenario C						
LHV, kJ/kg	13158,49	13158,49	13158,49	13158,49	13158,49	13158,49
	Heat Loss due to Chemically Incomplete Combustion					
q3, %	0	0,2	0,4	0,6	0,8	1
q3, kJ/kg	0	26,31699	52,63398	78,95097	105,268	131,5849
CO density at normal conditions, kg/m3	1,249	1,249	1,249	1,249	1,249	1,249
LHV_{CO}, kJ/m3 CO	12648	12648	12648	12648	12648	12648
CO volume, m3 CO/kg fuel	0	0,002081	0,004161	0,006242	0,008323	0,010404
CO mass, kg CO/kg fuel	0	0,002599	0,005199	0,007798	0,010398	0,012997
CO mass, g CO/kg fuel	0,000	2,599	5,199	7,798	10,398	12,997
C in CO, kg C/kg fuel	0,000	0,001	0,002	0,003	0,004	0,006
C in fuel, kg C/kg fuel	0,316788	0,305088	0,305088	0,305088	0,305088	0,305088
C in CO2, kg C/kg fuel	0,317	0,304	0,303	0,302	0,301	0,300
CO2 in complete combustion, m3/kg	0,592394	0,570515	0,570515	0,570515	0,570515	0,570515
CO2 density at normal conditions, kg/m3	1,963	1,963	1,963	1,963	1,963	1,963
CO2 mass in complete combustion, kg CO2/kg fuel	1,1630	1,1200	1,1200	1,1200	1,1200	1,1200
C in CO2 in complete combustion, kg C/kg fuel	0,317	0,305	0,305	0,305	0,305	0,305
CO2 in uncomplete combustion, m3/kg	0,592394	0,568	0,566	0,564	0,562	0,560
CO2 density at normal conditions, kg/m3	1,963	1,963	1,963	1,963	1,963	1,963
CO2 mass in uncomplete combustion, kg CO2/kg fuel	1,1630	1,1159	1,1118	1,1077	1,1037	1,0996
C in CO2 in uncomplete combustion, kg C/kg fuel	0,317	0,304	0,303	0,302	0,301	0,300

Scenario D						
LHV, kJ/kg	20241,6	20241,6	20241,6	20241,6	20241,6	20241,6
	Heat Loss due to Chemically Incomplete Combustion					
q3, %	0	0,2	0,4	0,6	0,8	1
q3, kJ/kg	0	40,4831	80,9662	121,449	161,932	202,415
CO density at normal conditions, kg/m3	1,249	1,249	1,249	1,249	1,249	1,249
LHV_{CO}, kJ/m3 CO	12648	12648	12648	12648	12648	12648
CO volume, m3 CO/kg fuel	0	0,00320	0,00640	0,00960	0,01280	0,01600
CO mass, kg CO/kg fuel	0	0,00400	0,00800	0,01200	0,01599	0,01999
CO mass, g CO/kg fuel	0,000	3,999	7,997	11,996	15,995	19,993
C in CO, kg C/kg fuel	0,000	0,002	0,003	0,005	0,007	0,009
C in fuel, kg C/kg fuel	0,49037	0,49037	0,49037	0,49037	0,49037	0,49037
C in CO2, kg C/kg fuel	0,490	0,489	0,487	0,485	0,484	0,482
CO2 in complete combustion, m3/kg	0,91700	0,91700	0,91700	0,91700	0,91700	0,91700
CO2 density at normal conditions, kg/m3	1,963	1,963	1,963	1,963	1,963	1,963
CO2 mass in complete combustion, kg CO2/kg fuel	1,8002	1,8002	1,8002	1,8002	1,8002	1,8002
C in CO2 in complete combustion, kg C/kg fuel	0,491	0,491	0,491	0,491	0,491	0,491
CO2 in uncomplete combustion, m3/kg	0,91700	0,914	0,911	0,907	0,904	0,901
CO2 density at normal conditions, kg/m3	1,963	1,963	1,963	1,963	1,963	1,963
CO2 mass in uncomplete combustion, kg CO2/kg fuel	1,8002	1,7939	1,7876	1,7813	1,7751	1,7688
C in CO2 in uncomplete combustion, kg C/kg fuel	0,491	0,489	0,488	0,486	0,484	0,482

Appendix 2

Calculation of converted emissions.

	NO_x	SO_2	CO	CO_2	Total results	
Conversion factors						
Acidifying potential	0,022	0,031	-	-	-	kg acidifying potential equivalent
TOFP	1,220	-	0,110	-	-	kg TOFP equivalent
Particulate formation PM10	0,880	0,540	-	-	-	kg Particulate formation equivalent
Global warming potential	-	-	-	1,0	-	kg CO2 equivalent
Results scenario A						
Acidifying potential	2,174	0,0275	-	-	2,201	kg acidifying potential equivalent
TOFP	122,0	-	2,626	-	124,626	kg TOFP equivalent
Particulate formation PM10	88,0	0,4754	-	-	88,475	kg Particulate formation equivalent
Global warming potential	-	-	-	44,013	44,013	kg CO_2 equivalent
Results scenario B						
Acidifying potential	2,174	0,004	-	-	2,178	kg acidifying potential equivalent
TOFP	122,0	-	2,802	-	124,802	kg TOFP equivalent
Particulate formation PM10	88,0	0,074	-	-	88,074	kg Particulate formation equivalent
Global warming potential	-	-	-	47,574	47,574	kg CO2 equivalent
Results scenario C						
Acidifying potential	2,174	0,061	-	-	2,234	kg acidifying potential equivalent
TOFP	122,0	-	2,547	-	124,547	kg TOFP equivalent
Particulate formation PM10	88,0	1,046	-	-	89,046	kg Particulate formation equivalent
Global warming potential	-	-	-	43,239	43,239	kg CO2 equivalent
Results scenario D						
Acidifying potential	2,174	0,029	-	-	2,203	kg acidifying potential equivalent
TOFP	122,0	-	2,643	-	124,623	kg TOFP equivalent
Particulate formation PM10	88,0	0,498	-	-	88,498	kg Particulate formation equivalent
Global warming potential	-	-	-	44,543	44,543	kg CO2 equivalent