Agronomy Research **14**(S1), 1169–1179, 2016

Methodology for determining the mixing ratio of selected solid recovered fuels

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Abstract. Energy recovery is a preferable waste management method for waste that cannot be reused or recycled. For energy recovery, various types of waste with differing properties are being used, e.g. mixed municipal solid waste or end-of-life tires. To achieve a more stable and homogeneous characteristics of the waste derived fuels (RDF, SRF), they can be mixed in a number of ratios. The paper presents a methodology for determining the optimal mixing ratio of three selected waste derived fuels (mixed municipal solid waste, sewage sludge, end-of-life tires) considering environmental and economic aspects. The developed method is based on combining life cycle assessment method, mass balance calculations and multi-criteria analysis (the technique for order of preference by similarity to ideal solution – TOPSIS). The results show that mixing the various waste derived fuels allows obtaining a more sustainable solution than in the case of each separate waste derived fuel.

Key words: Life cycle assessment, end-of-life tires, method integration, multi-criteria analysis, municipal solid waste, sewage sludge.

INTRODUCTION

Energy recovery from waste has become a popular management method for municipal solid waste (MSW). In the Baltic States, new municipal waste sorting plants are being opened, where solid recovered fuel (SRF) is produced. Lithuania is in the process of opening nine mechanical-biological treatment (MBT) facilities that will serve the whole country. In the country, one waste incineration plant is in operation, where refuse derived fuel (RDF) and SRF can be incinerated. Meanwhile Estonia has planned opening of four MBT plants (EEA, 2013), while a combined heat and power plant with waste mass incineration has been opened in 2013 near Tallinn (Eesti Energia, 2014). In Latvia, ten MBT plants have been set into operation (Dace et.al., 2015). The primary aim of the MBT plants is to pre-treat wastes prior to landfilling. Though, as a secondary target generation of RDF is considered (Dace & Blumberga, 2012). Currently in Latvia no waste incineration plants are installed or planned, except for a cement kiln that uses RDF and end-of-life tires for fuel (MEPRD, 2012).

In the study by Malijonyte et al. (2016), life cycle assessment (LCA) scenarios were developed for assessing the environmental impact and potential benefits generated during the gate-to-gate life cycle of preparation of the end-of-life (EoL) tires, SRF produced from MSW, and SRF produced from separate fraction of pre-composted sewage sludge and biomass residues. It was concluded that energy recovery from EoL tires generates the lowest environmental impact among the selected scenarios. Yet, a relatively small amount of EoL tires is generated as compared to MSW or sludge. While SRF from MSW or from sludge are low quality fuels to be incinerated alone. Therefore, a solution would be to mix SRF with other type of fuel or waste that has a higher calorific value, e.g. EoL tires.

Benefits obtained by increasing the calorific value of SRF should be balanced with energy inputs for producing the fuel, and with environmental impacts and economic costs and benefits. LCA allows for evaluating the environmental aspects, while evaluation of economic aspects is limited. The aim of this study is to develop a methodology that assists in selecting an optimal strategy for waste fuel mixing by considering the environmental, economic and energy aspects.

MATERIALS AND METHODS

The logical framework of the method proposed within this study is shown in Fig. 1. The starting point is the statement of a problem, which, in this specific study, has been addressed towards enhancing energy recovery from waste fuels by combining them together according to an estimated mixing ratio.

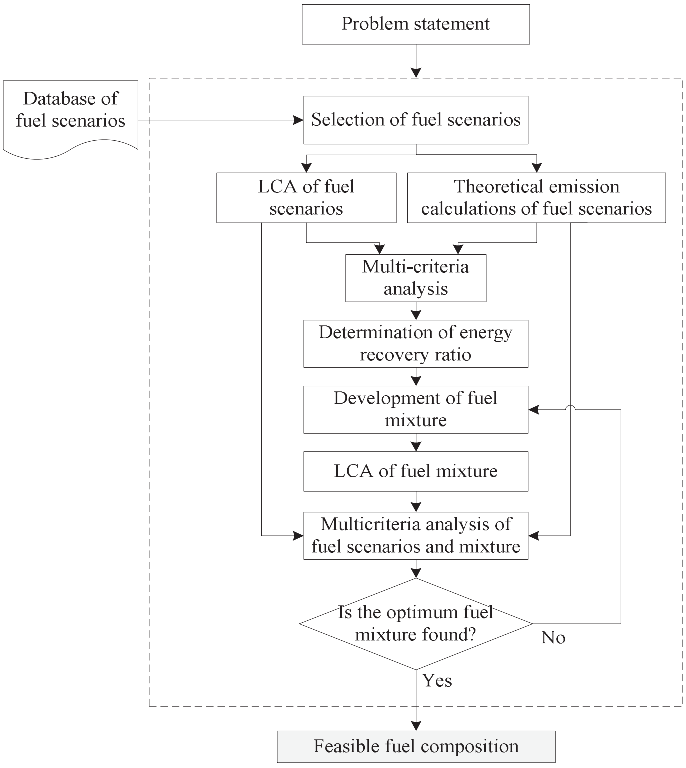

Figure 1. Logical framework of the method.

First stage of the methodology consists of selecting several potential waste fuel scenarios and conducting LCA of their production processes (described in detail by Malijonyte et al., 2016). Then, impact of processes outside LCA boundaries (in this study – waste incineration and outputs generated during the incineration process) are estimated by applying a theoretical calculations method. Further, the results obtained in LCA and theoretical calculations method are used for conducting multi-criteria analysis, where a technique for order preference by similarity to ideal solution (TOPSIS) is applied to compare the selected scenarios. TOPSIS is based on the concept that the best alternative should be as close as possible to the ideal solution, as the obtained results allow selecting the best of a finite number of alternatives (Dace et al., 2014). Current method is selected as it is suitable for combining different results for receiving a numerical output of preference ranking.

Application of the numerical preference ranking facilitates estimating the optimum mixing ratio of the selected waste fuel scenarios. LCA and theoretical calculations method is applied to estimate the impact of the fuel mixture and assessed again by conducting the multi-criteria analysis, this time by comparing with the initially developed waste fuel scenarios. If the developed fuel mixture demonstrates high environmental and economic performance then the initial fuel scenarios, it is selected for the feasible fuel composition.

The methodology of theoretical calculations, multi-criteria analysis and fuel mixing ratio is described in more detail in the following subsections.

Theoretical calculations of incineration outputs

The theoretical calculations include incineration process, during which ash and emissions to air are generated as process outputs. Each output is estimated separately, applying equations 1–7 (Nagla et al., 1981). The amount of produced ash is estimated according to the amount of fuel incinerated and ash content in the material (see Eq. 1).

$$\mathrm{M_{ash}} = (\mathrm{M_{fuel}} \cdot \mathrm{A^r})/100\% \qquad (1)$$

where: M_{ash} – mass of generated ash, kg; M_{fuel} – mass of fuel, kg; A^r – ash content in fuel as received, %.

In the study the main emissions estimated are SO_2, N_2, CO, CO_2 and NO_x. Volume of SO_2 (in $m^3\ kg^{-1}$) produced during the incineration of fuel is calculated using Eq. 2.

$$\mathrm{V_{SO_2}} = 0.0069 \cdot \mathrm{S^r} \qquad (2)$$

where: S^r – sulphur content in fuel as received, %.

Volume of N_2 (in $m^3\ kg^{-1}$) produced during incineration of fuel is calculated according to the Eq. 3.

$$\mathrm{V_{N_2}} = \mathrm{V^o_{N_2}} + 0.79\,(\alpha - 1) \cdot \mathrm{V^o} \qquad (3)$$

where: $V^o_{N_2}$ – theoretical volume of nitrogen, when $\alpha = 1$, defined within the Eq. 4, $m^3\ kg^{-1}$; α – air excess coefficient (real case $\alpha > 1$, selected value for solid fuels $\alpha = 1.4$); V^o – necessary theoretical amount of air, calculated by Eq. (5), $m^3\ kg^{-1}$.

$$V_{N_2}^{o} = 0.79 \cdot V^{o} + 0.008 \cdot N^{r} \quad (4)$$

$$V^{o} = 0.0889(C^{r} + 0.375 \cdot S^{r}) + 0.265 \cdot H^{r} - 0.0333 \cdot O^{r} \quad (5)$$

where: H^r – hydrogen content in fuel as received, %; N^r – nitrogen content in fuel as received, %; O^r – oxygen content in fuel as received, %.

The heat losses q_3 in the furnace due to chemically incomplete combustion have been considered. The value of q_3 normally ranges from 0 to 1.0%. In the calculations, several scenarios are assessed, where q_3 increases by 0.2%.

Volume of CO_2 (in $m^3\ kg^{-1}$) produced during incineration of fuel is calculated as follows:

$$V_{CO_2} = 0.01866 \cdot C^{r} \quad (6)$$

where: C^r – carbon content in fuel as received, %.

The main parameters used for calculations are $\rho_{CO} = 1.249\ m^3\ kg^{-1}$ (density at normal conditions); $LHV_{CO} = 12{,}648\ kJ\ m^{-3}$; $LHV_{fuel} = 33{,}353.5\ kJ\ kg^{-1}$. The total mass of NO_x is calculated using Eq. 7 (Charkov, 1997).

$$M_{NO_x} = 0.001 \cdot B \cdot LHV_{fuel} \cdot K_{NO_x} (1 - \beta), t \quad (7)$$

where: B – incinerated amount of fuel, kg; K_{NOx} – parameter characterizing amount of released nitrogen oxides, during production of 1 GJ of heat energy, $K_{NOx} = 0.1\ kJ\ kg^{-1}$; β – coefficient depending on nitrogen oxides emissions decreasing due to technological modifications, $\beta = 0$; LHV_{fuel} – lower heating value of the selected fuel, $MJ\ kg^{-1}$.

Multi-criteria analysis

To carry out the method, a decision matrix is constructed where *m* (row dimension) represents the set of fuel scenario alternatives (scenarios A-C) and *n* (column dimension) represents the selected criteria in terms of: LCA results for each scenario, amount of produced ash estimated by theoretical calculations, calculated air emissions, which are converted using corresponding equivalents and economic costs. Economic costs are selected within an average value of produced SRF cost in the market and costs of treatment, usually applied within waste treatment facilities. Thus, the selected criteria are LCA result (mPt), amount of ash (kg), CO_2 emission equivalent (kg), acidifying potential equivalent (kg), Tropospheric ozone forming potentials (TOFP) equivalent (kg), particulate formation equivalent (kg), produced fuel cost (Euro), and avoided waste treatment cost (Euro). The calculated air emissions are converted using suitable equivalents. Conversion data are presented in Table 1. Using converted units it is possible to sum up values of the emission equivalents of same environmental issue and to compare the scenarios to each other in a simplified way. An exception is applied to CO_2 equivalent results for scenario C where SRF consists of renewable sources, thus being a 'carbon neutral' fuel (Kliopova & Makarskienė, 2015).

Table 1. Conversion to equivalents data (De Leeuw, 2002)

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 PM_{10}	0.540	kg Particulate formation equivalent
NO_x	Particulate formation PM_{10}	0.880	kg Particulate formation equivalent

The next step of the applied TOPSIS technique, is to construct the normalized decision matrix, where various criteria dimensions are transformed into non-dimensional criteria, what allows comparison across the criteria. To determine normalized decision matrix Eq. 8 is applied.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{8}$$

Then the weighted normalized decision matrix is constructed – each column of the normalized decision matrix is multiplied by its weight w_j, to get v_{ij}. Weight for each criterion is assigned by the importance or dangers to the environment (see Table 2).

Table 2. Weight for each criterion

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

After weighted normalized decision matrix is completed, ideal and negative-ideal solutions are determined. First, 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. Second, 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.

Further, 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. 9. Separation from negative-ideal solution S_i^- is calculated analogically by applying Eq. 9.

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij}^* - v_{ij})^2} \tag{9}$$

After determination of separation values, the relative closeness to the ideal solution is calculated using the following equation:

$$c_i^* = \frac{S_i^-}{(S_i^+ + S_i^-)} \tag{10}$$

where: $0 < c_i^+ < 1$; $c_i^* = 1$ 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^*.

Determination of fuel mixture ratio

The ranking results are used for determining the energy recovery ratio ER_i (Eq. 11) for each initial fuel scenario.

$$ER_i = c_i^* \cdot 100\% \Big/ \sum c_i^* \tag{11}$$

According to the amount of recovered energy by each fuel, mass of the fuel in the mixture is calculated and final SRF mixture ratio is estimated.

Characterisation of the fuel mixture

An LCA study is carried out on the preparation of the obtained fuel mixture. Data from the initial LCA scenarios presented by Malijonyte et al. (2016) are used. For the mixture, to generate 1 GJ of fuel input all initial fuel scenarios (A, B, and C) are used, according to the fuel mix composition. According to amount of recovered energy by each fuel scenario, mass of the fuel is calculated. Characteristics of the fuel mixture are calculated with respect to the share of each initial fuel scenario. Generated environmental impact by 1 GJ fuel input production using fuel mixture is allocated according to the share of each initial fuel scenario. Finally, the performance of the fuel mixture (scenario D) is compared with the performance of each individual fuel scenario (scenarios A, B and C) by applying the same criteria that were used in the multi-criteria analysis stage.

RESULTS AND DISCUSSION

Results of theoretical emission calculations

The results of the theoretical emission calculations are presented in Table 3. The scenarios assessed are as follows: A – shredded EoL tires, B – SRF from MSW, and C – SRF from separate fraction of pre-composted sewage sludge and biomass residues. The functional unit (FU) used for calculations is 1 GJ of fuel energy.

Table 3. Theoretical calculations results per functional unit (kg FU^{-1})

Scenario	Ash	SO_2	CO	CO_2	N_2	NO_x
A	1.193	0.742	23.565	44.013	359.416	100.00
B	14.070	0.137	25.472	47.574	350.305	100.00
C	20.490	1.937	23.150	42.238	363.590	100.00

It can be seen that the amount of produced ash in scenario A is significantly lower, compared to scenarios B and C. This is due to the low ash content in EoL tires (about

4%) and the comparatively low amount of fuel necessary for ensuring 1GJ of fuel energy. The largest difference among scenarios is for SO_2 emissions. In scenario B, SO_2 emissions are the lowest, while for scenario C they reach 1.94 kg per FU. The amount of SO_2 depends only on sulphur content in the fuel. Results for CO, CO_2 and N_2 emissions are very close for all scenarios. NO_x emissions for all scenarios are the same, as they are estimated by the amount of heat produced. It has to be noted, that, in scenario C, CO_2 emissions assumed to be 'carbon neutral', as the fuel consists of renewable bio-sources (Kliopova & Makarskienė, 2015).

Results of multi-criteria analysis of scenarios preference

Corresponding to the selected criteria and results for each criterion given by scenarios A, B, and C, a decision matrix was created (see Table 4), followed by generating the normalized decision matrix r_{ij} (see Table 5), and the weighted normalized decision matrix v_{ij} (see Table 6).

Table 4. Decision matrix

	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
A	1.460	1.193	44.013	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

Table 5. Normalized decision matrix

Scenario	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
A	0.026	0.048	0.679	0.576	0.577	0.577	0.836	0.546
B	0.833	0.565	0.734	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

Table 6. Weighted normalized decision matrix

Scenario	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
A	0.008	0.002	0.102	0.058	0.058	0.058	0.084	0.055
B	0.250	0.028	0.110	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 the following TOPSIS step, results for the ideal solution A^+ and negative-ideal solution A^- were determined for each criterion:

$A^+ = \{0.008, 0.002, 0.000, 0.057, 0.058, 0.057, 0.035, 0.074\}$

$A^- = \{0.250, 0.041, 0.110, 0.059, 0.058, 0.058, 0.084, 0.039\}$

The obtained results for separations from the ideal solutions, S_i^+ and S_i^-, and the relative closeness to the ideal solution, c_i^*, for each scenario are presented in Table 7. The selected energy recovery scenarios are ranked by preference according to the descending order of c_i^*.

Table 7. Separations from ideal solution and ranking results

Scenario	S_i^+	S_i^-	c_i^*	Preference
A	0.114	0.246	0.682	Best
B	0.270	0.043	0.139	Worst
C	0.163	0.151	0.481	

The preference ranking results allow us to conclude that energy recovery from EoL tires is the most preferable having the highest ranking result. Recovering energy from fuel scenario C is the second most preferable, although having small disparity from scenario A. Finally, energy recovery from SRF produced from MSW (scenario B) is the least preferable with significantly lower result.

Fuel mixture ratio and characteristics

Based on the TOPSIS ranking results, the energy recovery ratio, ER_i, was determined. Based on that, the optimum fuel mixture ratio was created (see Table 8).

Table 8. Composition of the estimated feasible fuel mix

Scenario	ER_i, %	Energy recovered, MJ	LHV, MJ kg^{-1}	Fuel mass, kg	SRF mixture ratio, %
A	52.406	524.062	33.353	15.713	30.967
B	10.640	106.404	15.327	6.942	13.682
C	36.953	369.534	13.158	28.084	55.350

Characterisation results of the fuel mix are presented in Table 9, while the incineration emissions and generated amount of ash estimated by applying the theoretical calculations method are presented in Table 10.

Table 9. Characteristics of the fuel mixture

Fuel	Composition, wt. %							HHV,	LHV,
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash	Moisture	MJ kg^{-1}	MJ kg^{-1}
MIX	47.913	5.398	16.405	1.395	1.134	18.899	8.856	21.358	19.922

Table 10. Theoretical calculations results for the fuel mixture per functional unit (kg FU^{-1})

	Ash	SO_2	CO	CO_2	N_2	NO_x
MIX	9.486	1.121	23.868	44.578	360.067	100.00

LCA and TOPSIS results of all four scenarios

Using inventory data (see Appendix 1), gate-to-gate life cycle for energy recovery from mixed SRF was created. The network includes processes used for modelling of the individual scenarios (see the study by Malijonyte et al. (2016)). The LCA results show, that the impact created by producing the fuel mixture with 1 GJ of fuel energy input is 16.6 mPt. If compared with the impact result of the initial scenarios A, B and C, the obtained result of the fuel MIX is lower than in scenarios B (46.74 mPt) and C (31.0 mPt), but higher that in scenario A (1.46 mPt) (see Fig. 2).

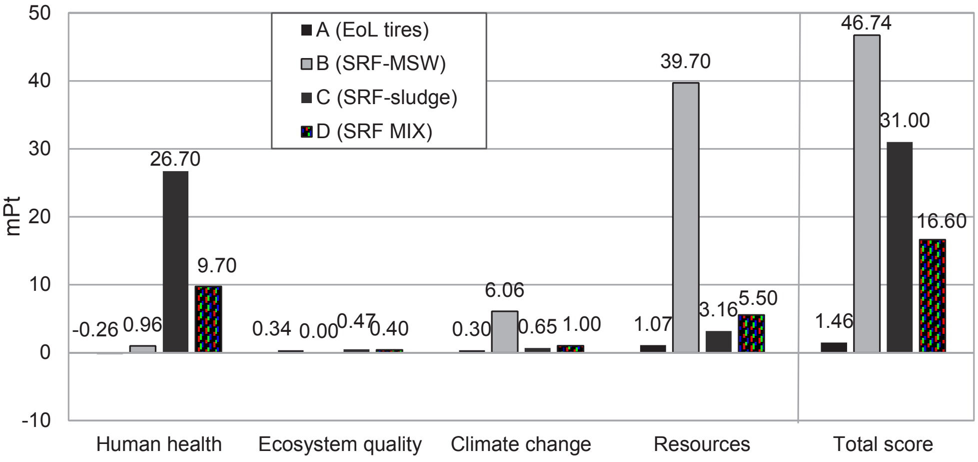

Figure 2. LCA results of fuels A, B, C and MIX.

In scenario MIX, the largest impact is generated the fraction of SRF-sludge, as it composes more than half of the fuel mixture's mass and requires electric energy for dewatering and pelleting processes. Another large part of the impact is generated by the fraction of SRF-MSW that requires a set of treatment processes. Biomass transportation has slightly lower impact than MSW treatment. The remaining processes, such as shredding of EoL tires, pre-composting of sludge and biomass, and material transportation generate relatively small environmental impact. Some of the processes are not visible in the network, as processes creating minor impact are cut-off. Yet, impact by cut-off processes is included in the final result.

Results show, that impact on human health created by SRF-sludge is reduced approximately 5 times in the case of fuel MIX by adding other fuel types in the mixture (EoL tires, SRF-MSW). Whereas, the presence of SRF-MSW increases the overall impact of fuel MIX on resource depletion. Impact of the fuel MIX on ecosystem quality and climate change does not differ much from the impact of other scenarios, and is comparatively low.

The results of the multi-criteria analysis of all four scenarios are presented in Table 11. The preference ranking results show that the fuel MIX has the second highest preference after the EoL tires.

Table 11. Ranking results of all four scenarios

Scenario	c_i^*	Preference
A	0.712	Best
B	0.129	Worst
C	0.460	
MIX	0.558	2nd best

CONCLUSIONS

In this paper, a methodology is proposed, where LCA and multi-criteria analysis methods are integrated for determination of the optimum mixing ratio of selected solid recovered fuels for energy recovery. Four scenarios using different waste fuels have been compared. 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. Results of the multi-criteria analysis formed the basis for finding the optimum fuel mixing ratio to be evaluated by LCA. The LCA results indicated that the impact of the developed fuel mixture is lower than the impact of individually used SRF from MSW or SRF from sludge. Finally, additional multi-criteria analysis of all four fuel scenarios indicated that the developed fuel mixture is more preferable than SRF from MSW or SRF from sludge. Thus, mixing higher quality less-available fuel (EoL tires) 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.

ACKNOLEDGEMENT. The work has been supported by the National Research Program 'Energy efficient and low-carbon solutions for a secure, sustainable and climate variability reducing energy supply (LATENERGI)'.

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APPENDICES

Appendix 1. Inventory analysis for preparation of fuel mixture

Material	Amount	Unit
Input		
End-of-life tires	20.099	kg FU^{-1}
Municipal solid waste	17.535	kg FU^{-1}
Sewage sludge	70.302	kg FU^{-1}
Biomass waste	70.302	kg FU^{-1}
Transportation	Amount	unit
Transport tires (collection points to shredding facility)	5.045	tkm[1]
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^{-1}
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^{-1}
Input		
Lubricating oil	0.0045	kg FU^{-1}
Electricity mix	4.165	kWh FU^{-1}
Output (waste to treatment)		
Inert waste	0.563	kg FU^{-1}
Scrap metal (for recycling)	3.649	kg FU^{-1}
MSW treatment in MBT	17.535	kg FU^{-1}
Input		
Electricity mix	45.933	kWh FU^{-1}
Output (waste to treatment)		
Paper and cardboard (recycling)	0.594	kg FU^{-1}
Plastic (recycling)	1.365	kg FU^{-1}
Glass (recycling)	0.765	kg FU^{-1}
Metals (recycling)	0.393	kg FU^{-1}
Other waste not suitable for treatment (landfilling)	0.526	kg FU^{-1}
SRF pre-composting	140.604	kg FU^{-1}
Input		
Diesel for Residues milling, composting,	0.068	kg FU^{-1}
Water	0.014	m^3 FU^{-1}
Industrial oil	0.0013	kg/FU
Output		
Compost for further composting	32.029	kg FU^{-1}
Waste water	0.052	m^3 FU^{-1}
Dewatering and pelleting of SRF	27.793	kg FU^{-1}
Input		
Electricity mix	0.156	kWh FU^{-1}
Water	0.014	m^3 FU^{-1}
Output		
Waste water	0.014	m^3 FU^{-1}
PM emissions from pelleting process	0.551	kg FU^{-1}

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[1] tkm – ton-kilometre, a unit quantifying freight transportation, which represents the transport of one ton of waste over a distance of one kilometre