Supplementary material

to the article:

Life Cycle Assessment of Different Waste Lubrication Oil Management Options in Serbia

(authors: Ljubica Duđak, Stevan Milisavljević, Mitar Jocanović, Ferenc Kiss, Dragoljub Šević, Velibor Karanović, Marko Orošnjak)

submitted to **Applied Sciences.**

Appendix A:

Inventory of the analysed processes

Contents

Table A1: Inventory of the five WLO re-refining technologies (Cyclon, Evergreen, Puralube, MRD, Viscolube) considered in the IFEU study (Fehrenbach, 2005, p. 22)

	Process 1	**Process 2**	**Process 3**	**Process 4**	**Process 5**	
Input						Unit
Used oil	1000	1000	1000	1000	1000	kg
Auxiliaries						
caustic soda	4.67	10		0.71	2.69	kg
potassium hydroxide			0.06			kg
hydrogen	5.16	4.32		2.02	0.30	kg
nitrogen					1.42	kg
Soda	8.41					kg
propane				2.25		kg
n-Methylpyrrolidon			0.06			kg
energy demand						
electricity	875	226	122	283	223	MJ
process heat	1360 [a)]		622	2420		MJ
process heat (gross demand)		2020 [b)]			3390 [b)]	MJ
process heat (net demand)		264 [b)]			*902* [b)]	MJ
process steam	632	2360 [c)]	1630	617	216 [a)]	MJ
process water	374				360	kg
Output						
base oil	770.8	694.9	544.5	725.2	695.6	kg

Naphtha	37.6					kg
light ends		47.0 d)	25.0 e)	14.2 e)	141.0 h)	kg
extracts			78.0 e)			kg
flux oil			29.3 h)	82.2 h)		kg
light fuel oil	75.2 f)			99.2 e)		kg
gas oil		68.6 f)			37.6 g)	kg
heavy oil	56.4 i)		137.3 e)		65.8 j)	kg
bitumen additive		134.8 k)				kg
Residue			123.6 i)			kg
used process water	433.8	60	59.7	79	420	kg
net energy deliverance process heat			7500	707 l)		MJ

Explanatory legend:

a) Process heat and steam is produced by a natural gas fired furnace resp. boiler

b) After combustion of light ends (a) and covering partly the "gross" demand on process heat there rests a "net demand". This is normally covered by by-products of other refining sites of the company. For this balancing natural gas firing is applied to avoid additional complications due to allocation.

c) Steam is produced also by by-products. Here is also natural gas firing presumed.

d) Light ends (naphtha quality) are applied as fuel on the regeneration site and cover partly the process heat demand (input: "gross demand" minus "net demand").

e) Light ends, extracts and fuel oil (DIN quality) is applied as fuel on the regeneration site; they cover the process heat and process steam demand (input) and leave a "*net energy deliverance*" (Output).

f) Gas oil (Diesel quality) applied as fuel off the regeneration site but within the system boundary; equivalency process is a light fuel oil combustion with pre chain.

g) Diesel quality; equivalency process is production of hydro finished diesel

h) “Flux oil”, residues and light ends are applied as additive to bitumen; equivalency process is an appli- cation of vacuum distillate (flux oil) with pre chain.

i) Heavy oil and residues are applied as reduction material within a blast furnace; equivalency process is an application of heavy fuel oil with pre chain.

j) Heavy oil is applied on-site as fuel and covers partly the process heat demand (input: “gross demand” minus “net demand”).

k) Residues are applied within the manufacture of bitumen layers; equivalency process is an application of bitumen distillate with pre chain and partly of polypropylene fibres (1 kg of residue substitutes 1 kg of bitumen and allows in addition to reduce the polypropylene demand about 420 g.

l) After combustion of light ends and light oil (a) and covering the process demand on heat, this amount is another benefit of the process; equivalency process is a fuel oil combustion with pre chain.

Table A2: Material and energy flow associated with the first re-refining technology (*ReR1*) and the respective LCI datasets (as used in this study) (based on Fehrenbach, 2005, p. 22)

	Process 1		LCI data (ecoinvent 3.7 cut-off)
Input		Unit	
Used oil	1000	kg	assumed to be burden free in accordance with the cut-off modeling principles
Transport of used oil to cement kilns [a)]	200	tkm	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – RER (ecoinvent 3.7 cut-off process)
Auxiliaries			
caustic soda	4.67	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO
hydrogen	5.16	kg	market for hydrogen, gaseous | hydrogen, gaseous | Cutoff, U - GLO
Soda	8.41	kg	market for soda ash, dense | soda ash, dense | Cutoff, U - GLO
energy demand			
electricity	875	MJ	market for electricity, low voltage | electricity, low voltage | Cutoff, U - RS
process heat	1360	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U – GLO
process steam	632	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RER

process water	374	kg	market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland
Output			
base oil	770.8	kg	base oil production, petroleum refinery operation | base oil | Cutoff, U - Europe without Switzerland [b)]
Naphtha	37.6	kg	naphtha production, petroleum refinery operation | naphtha | Cutoff, U - Europe without Switzerland [b)]
light fuel oil	75.2	kg	light fuel oil production, petroleum refinery operation | light fuel oil | Cutoff, U - Europe without Switzerland [b)]
heavy oil	56.4	kg	heavy fuel oil production, petroleum refinery operation | heavy fuel oil | Cutoff, U - Europe without Switzerland [b)]
used process water	433.8	kg	treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland

Notes: a) It is assumed that the average distance between collection centers and waste treatment facility is 100 km. b) Avoided process.

Table A3: Material and energy flow associated with the second re-refining technology (*ReR2*) and the respective LCI datasets (as used in this study) (based on Fehrenbach, 2005, p. 22)

	Process 2		LCI data (ecoinvent 3.7 cut-off)
Input		Unit	
Used oil	1000	kg	assumed to be burden free in accordance with the cut-off modeling principles
Transport of used oil to cement kilns [a)]	200	tkm	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – RER (ecoinvent 3.7 cut-off process)
Auxiliaries			
caustic soda	10	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO
hydrogen	4.32	kg	market for hydrogen, gaseous | hydrogen, gaseous | Cutoff, U - GLO
energy demand			
electricity	226	MJ	market for electricity, low voltage | electricity, low voltage | Cutoff, U - RS
process heat	1756	MJ	heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland
process heat	264	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U – GLO

process steam	2360	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RER
process water		kg	market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland
Output			
base oil	694.9	kg	base oil production, petroleum refinery operation | base oil | Cutoff, U - Europe without Switzerland [b)]
light ends [c)]	0	kg	
gas oil	68.6	kg	light fuel oil production, petroleum refinery operation | light fuel oil | Cutoff, U - Europe without Switzerland [b)]
bitumen additive	134.8	kg	bitumen seal production | bitumen seal | Cutoff, U - RER [b)]
used process water	60	kg	treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland

Notes: a) It is assumed that the average distance between collection centers and waste treatment facility is 100 km. b) Avoided process. c) as suggested by Fehrenbach (2005, p. 22) light ends are applied as fuel on the regeneration site and cover partly the process heat demand (input: “gross demand” minus “net demand”).

Table A4: Material and energy flow associated with the third re-refining technology (*ReR3*) and the respective LCI datasets (as used in this study) (based on Fehrenbach, 2005, p. 22)

	Process 3		LCI data (ecoinvent 3.7 cut-off)
Input		Unit	
Used oil	1000	kg	assumed to be burden free in accordance with the cut-off modeling principles
Transport of used oil to cement kilns [a)]	200	tkm	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – RER (ecoinvent 3.7 cut-off process)
Auxiliaries			
potassium hydroxide	0.06	kg	market for potassium hydroxide | potassium hydroxide | Cutoff, U - GLO
n-Methylpyrrolidon	0.06	kg	market for N-methyl-2-pyrrolidone | N-methyl-2-pyrrolidone | Cutoff, U - GLO
energy demand			
electricity	122	MJ	market for electricity, low voltage | electricity, low voltage | Cutoff, U - RS
process heat	622	MJ	heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland
process steam	1630	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RER
Output			

base oil	544.5	kg	base oil production, petroleum refinery operation | base oil | Cutoff, U - Europe without Switzerland [b)]
light ends [c)]	0	kg	
extracts [c)]	36.2	kg	light fuel oil production, petroleum refinery operation | light fuel oil | Cutoff, U - Europe without Switzerland [b)]
flux oil	29.3	kg	bitumen seal production | bitumen seal | Cutoff, U - RER [b)]
heavy oil	137.3	kg	heavy fuel oil production, petroleum refinery operation | heavy fuel oil | Cutoff, U - Europe without Switzerland [b)]
Residue	123.6	kg	heavy fuel oil production, petroleum refinery operation | heavy fuel oil | Cutoff, U - Europe without Switzerland [b)]
used process water	59.7	kg	treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland

Notes: a) It is assumed that the average distance between collection centers and waste treatment facility is 100 km. b) Avoided process. c) as suggested by Fehrenbach (2005, p. 22) light ends, extracts and fuel oil (DIN quality) are applied as fuel on the regeneration site; they cover the process heat and process steam demand (input). In this study it was assumed that light ends and extracts have heating value as light fuel oil and are used to generate process heat and steam. 0.0246 kg and 0.0315 kg of light fuel oil is required to generate 1 MJ of heat and steam (data from the ecoinvent 3.7 database), respectively. Therefore, 15.33 kg of light ends/extracts is used to generate process heat, and 51.46 kg light ends/extracts is used to generate the process steam. This gives a surplus of 36.2 kg light ends/extracts from the process.

Table A5: Material and energy flow associated with the fourth re-refining technology (*ReR4*) and the respective LCI datasets (as used in this study) (based on Fehrenbach, 2005, p. 22)

	Process 4		LCI data (ecoinvent 3.7 cut-off)
Input		Unit	
Used oil	1000	kg	assumed to be burden free in accordance with the cut-off modeling principles
Transport of used oil to cement kilns [a)]	200	tkm	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – RER (ecoinvent 3.7 cut-off process)
Auxiliaries			
caustic soda	0.71	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO
hydrogen	2.02	kg	market for hydrogen, gaseous | hydrogen, gaseous | Cutoff, U - GLO
propane	2.25	kg	market for propane | propane | Cutoff, U - GLO
electricity	283	MJ	market for electricity, low voltage | electricity, low voltage | Cutoff, U - RS
process heat	2420	MJ	heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland
process steam	617	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RER
Output			

base oil	725.2	kg	base oil production, petroleum refinery operation | base oil | Cutoff, U - Europe without Switzerland [b)]
light ends [c)]	0	kg	
flux oil	82.2	kg	bitumen seal production | bitumen seal | Cutoff, U - RER [b)]
light fuel oil [c)]	17.4	kg	light fuel oil production, petroleum refinery operation | light fuel oil | Cutoff, U - Europe without Switzerland [b)]
used process water	79	kg	treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland

Notes: a) It is assumed that the average distance between collection centers and waste treatment facility is 100 km. b) Avoided process. c) as suggested by Fehrenbach (2005, p. 22) light ends are applied as fuel on the regeneration site; they cover the process heat and process steam demand (input). The surplus, after satisfying process heat and steam requirements, is 17.4 kg of light fuel oil.

Table A6: Material and energy flow associated with the fifth re-refining technology (*ReR5*) and the respective LCI datasets (as used in this study) (based on Fehrenbach, 2005, p. 22)

	Process 5		LCI data (ecoinvent 3.7 cut-off)
Input		Unit	
Used oil	1000	kg	assumed to be burden free in accordance with the cut-off modeling principles
Transport of used oil to cement kilns [a)]	200	tkm	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – RER (ecoinvent 3.7 cut-off process)
Auxiliaries			
caustic soda	2.69	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO
hydrogen	0.30	kg	market for hydrogen, gaseous | hydrogen, gaseous | Cutoff, U - GLO
nitrogen	1.42	kg	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RER
energy demand			
electricity	223	MJ	market for electricity, low voltage | electricity, low voltage | Cutoff, U - RS
process heat	902	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U – GLO

process heat	2488	MJ	heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland
process steam	216	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RER
process water	360	kg	market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland
Output			
base oil	695.6	kg	base oil production, petroleum refinery operation | base oil | Cutoff, U - Europe without Switzerland [b)]
light ends	141.0	kg	bitumen seal production | bitumen seal | Cutoff, U - RER [b)]
gas oil	37.6	kg	bitumen seal production | bitumen seal | Cutoff, U - RER [b)]
heavy oil [c)]	0	kg	
used process water	420	kg	treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland

Notes: a) It is assumed that the average distance between collection centers and waste treatment facility is 100 km. b) Avoided process. c) as suggested by Fehrenbach (2005, p. 22) heavy oil is applied on-site as fuel and covers partly the process heat demand (input: “gross demand” minus “net demand”).

Table A7: Inventory of material and energy flows associated with the burning of WLO in cement kilns (CemK process)

	Amount	Unit	LCI data
Inputs			
Used oil	1000	kg	assumed to be burden free in accordance with the cut-off modeling principles
Transport of used oil to cement kilns [a)]	200	tkm	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – RER (ecoinvent 3.7 cut-off process)
Outputs			
Heat [b)]	40	GJ	Avoided process is the same amount of heat generated by combustion of petroleum coke (see Table A8)
Emissions to air			
Arsenic [b)]	2.00E-08	kg	elementary flow
Cadmium [b)]	1.30E-06	kg	elementary flow
Carbon dioxide, fossil [b)]	2933	kg	elementary flow
Carbon monoxide, fossil [c)]	16.1	kg	elementary flow
Chromium [b)]	1.60E-08	kg	elementary flow
Nickel [b)]	4.30E-07	kg	elementary flow
Nitrogen oxides [c)]	5.1	kg	elementary flow
NMVOC [c)]	5	kg	elementary flow
Sulfur dioxide [b)]	0.13	kg	elementary flow

Notes: a) It is assumed that the average distance between collection centers and waste treatment facility is 100 km.b) Fehrenbach, 2005 (Table 6-11, p. 35). c) Pires and Martinho (2013).

Table A8: Inventory of material and energy flows associated with heat generation from petroleum coke

	Amount	Unit	LCI data
Inputs			
Petroleum coke [a)]	1076	kg	market for petroleum coke | petroleum coke | Cutoff, U – GLO (ecoinvent 3.7 cut-off process)
Outputs			
Heat [b)]	40	GJ	reference flow
Emissions to air [b)]			
Arsenic	1.72E-04	g	elementary flow
Cadmium	0.00108	g	elementary flow
Carbon dioxide, fossil	3630	kg	elementary flow
Chromium	5.38E-05	g	elementary flow
Nickel	0.00215	g	elementary flow
Sulfur dioxide	0.43	kg	elementary flow

Notes: a) 1076 kg of petroleum coke delivers the same amount of heat as 1000 kg of WLO (Fehrenbach, 2005; Table 6-11, p. 35); b) Fehrenbach, 2005 (Table 6-11, p. 35)

Table A9: Inventory of material and energy flows associated with incineration of WLO with energy recovery (Inc1 process)

	Amount	Unit	LCI data
Inputs			
Used oil	1000	kg	assumed to be burden free in accordance with the cut-off modeling principles
Transport of used oil [a)]	200	tkm	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – RER (ecoinvent 3.7 cut-off process)
Other inputs [b)]	not shown here but available from the ecoinvent database		see treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U (ecoinvent 3.7 cut-off process)
Outputs			
Heat [c)]	25.82	GJ	market for heat, central or small-scale, natural gas | heat, central or small-scale, natural gas | Cutoff, U - Europe without Switzerland(ecoinvent 3.7 cut-off process) [d)]
Electricity [c)]	0.67	MWh	market for electricity, low voltage | electricity, low voltage | Cutoff, U – RS(ecoinvent 3.7 cut-off process)[d)]
Emissions to air and water [b)]	not shown here but available from the ecoinvent database		see treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U (ecoinvent 3.7 cut-off process)
Waste [b)]			see treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U (ecoinvent 3.7 cut-off process)

Notes: a) It is assumed that the average distance between collection centers and waste treatment facility is 100 km. b) types and amounts of other inputs, emissions to air and water, wastes are available from the ecoinvent 3.7 process: treatment of waste mineral oil, hazardous waste incineration \| waste mineral oil \| Cutoff, U; c) data from the ecoinvent 3.7 database (process name: treatment of waste mineral oil, hazardous waste incineration \| waste mineral oil \| Cutoff, U); d) avoided process.

Table A10: Inventory of material and energy flows associated with incineration of WLO without energy recovery (Inc2 process)

	Amount	Unit	LCI data
Inputs			
Used oil	1000	kg	assumed to be burden free in accordance with the cut-off modeling principles
Transport of used oil [a)]	200	tkm	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U – RER (ecoinvent 3.7 cut-off process)
Other inputs [b)]	not shown here but available from the ecoinvent database		see treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U (ecoinvent 3.7 cut-off process)
Outputs			
Emissions to air and water [b)]	not shown here but available from the ecoinvent database		see treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U (ecoinvent 3.7 cut-off process)
Waste [b)]			see treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U (ecoinvent 3.7 cut-off process)

Notes: a) It is assumed that the average distance between collection centers and waste treatment facility is 100 km. b) types and amounts of other inputs, emissions to air and water, wastes are available from the ecoinvent 3.7 process: treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U.

References

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