VDI Zentrum Ressourceneffizienz

Ecological and economic Assessment of Resource Expenditure

Water-miscible cooling Lubricants

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Study: Ecological and economic Assessment of Resource Expenditure - Water-miscible cooling Lubricants

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Ecological and economic Assessment of Resource Expenditure

Water-miscible cooling Lubricants

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADP	Abiotic Depletion Potential
AP	Acidification Potential
BAFA	Federal Office for Economic Affairs and Export Control
BSE	Bovine spongiform encephalopathy
BUBW	Betrieblicher Umweltschutz in Baden-Württemberg (Industrial Environmental Protection in Baden-Württemberg)
C.A.R.M.E.N.	Central Agricultural Raw Material and Energy Network
CED	Cumulative energy demand
CEN	Comité Européen de Normalization (European Committee for Standardization)
CH_4	Methane
CLP	Classification, Labelling and Packaging of Chemicals
CLs	Cooling lubricants
CML	Institute of Environmental Sciences
CO_2	Carbon dioxide
CRMD	Cumulative raw material demand
DERA	German Mineral Resources Agency
DIN	German industrial standard
ECHA	European Chemicals Agency
EC	European Community
EN	European Standard
EoL	End-of-life
EP	Eutrophication potential
EU	European Union
FAOSTAT	Food and Agriculture Organisation Statistics (Statistics of the World Food Organisation)
FU	Functional unit

FNR	Fachagentur Nachwachsende Rohstoffe (Agency for Renewable Resources)
GHG	Greenhouse gas
GWP	Global warming potential
HHI	Herfindahl-Hirschman Index
HM	Heavy metal
ISO	International Organisation for Standardization
JMTBA	Japan Machine Tool Builders' Association
MIN	Solvent raffinate
MQL	Minimum quantity lubrication
N_2O	Nitrous oxide
NP	Nutrification potential
nwmb	non-water miscible
OECD	Organisation for Economic Co-operation and Development
ODP	Ozone depletion potential
PAO	Polyalphaolefins
PCI	Political country risk indicator
PM	Particulate matter (particulate pollution potential)
POCP	Photochemical ozone creation potential (Photosmog)
RCI	Regulatory country risk indicator
RD	Resource demand
ReCiPe	Life-cycle impact assessment method
RiS	Raw materials in storage sites
RME	Rapeseed methyl ester
SMEs	Small and medium-sized enterprises
TR	Technical report
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
wmb	water-miscible

INTRODUCTION

Cooling lubricants (CLs) are very important in machining and forming metalwork. They increase the productivity and cost-effectiveness of the processes.

In the metalworking industry, water-miscible cooling lubricants are used in about 90% of machining processes.[1] They consist of a mostly mineral base oil and an additive package. In addition to innovative technologies such as minimum quantity lubrication or dry machining, the consumption of cooling lubricant and the associated costs and environmental impact can be reduced through resource efficiency measures. These include e.g. cooling lubricant care for service life extension or substitution of cooling lubricants with appropriate e.g. mineral oil-free alternatives.

The aim of the study is to research available abiotic and biotic base oil alternatives for water-miscible cooling lubricants and to quantify and compare their ecological and economic effects for a specific application. In relation to a functional unit to be defined,

- the consumption[2] of energy, raw materials, water, the required area and the emissions released in CO_2 equivalents over the entire life cycle are determined,
- the criticality of supply of base oil alternatives is evaluated and
- the resulting costs are accounted for from the point of view of the cooling lubricant user.

On methodological grounds, carrying out a comparative ecological and economic assessment requires an identical observation system and a functional unit. The observation system should also have the highest possible practical relevance. The milling process, which is used predominantly in industry for

1 See Betrieblicher Umweltschutz in Baden-Württemberg (2015a).

2 Determination of consumption is based on the VDI Guidelines 4800 Part 1 and 2 and VDI Guideline 4600.

machining metal workpieces, has therefore been selected as the metalworking process for the present study.[3]

Water-miscible cooling lubricants can be used in the form either of solutions or emulsions. For milling, the literature on materials processing, especially steel and cast iron processing, recommends the use of emulsions[4], which are used as the water-miscible cooling lubricants to be evaluated in the study.

The base oils used for the emulsions are classified into substances and oils of mineral origin or as substances and oils of animal and plant origin.[5] The substances and oils of mineral origin include the solvent raffinate (MIN). It is mainly used as a base oil and therefore serves as an alternative for the assessment.

As far as substances and oils of animal and vegetable origin are concerned, rapeseed methyl ester (RME) is used as an alternative base oil. Bio-based, water-miscible cooling lubricants are used as niche products[6] and have some advantages over mineral oil, such as higher tolerability in occupational health. Rapeseed oil often forms the basis for bio-based, water-miscible cooling lubricants. Transesterified rapeseed methyl ester as an emulsion tends to display faster microbial contamination and gumming, however, leading to a shorter service life, a fact which is included in the study by three corresponding scenarios in the assessment. However, since the composition or structure of bio-based, water-miscible CLs is usually subject to confidentiality for public studies for reasons of competition and it was only possible to research available data for rapeseed methyl ester for a life-cycle assessment, rapeseed methyl ester was used as a representative for bio-based, water-miscible cooling lubricants. In addition, the market for bio-based lubricants is still relatively young, so that it may be anticipated that future innovations will have a positive effect on the technical properties of rapeseed-oil-based cooling lubricants. [7]

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3 See Schischke, K. et al. (2012), pp. 12 et seqq.

4 See Betrieblicher Umweltschutz in Baden-Württemberg (2015e); Gomeringer, R. et al. (2014), p. 308.

5 See Brinksmeier, E. et al. (2015), p. 621.

6 See Riedel Schmierstoffe (2016) and Wascut Industrieöle GmbH (2001).

7 See Wascut Industrieöle GmbH (2001).

The spatial system limits of the scope of investigation for the base oil variants solvent raffinate and rapeseed methyl ester include

- the production phase (crude oil production, base oil production, production of the cooling lubricant concentrate),
- the utilisation phase and
- the disposal phase (emulsion splitting with thermal recovery from the waste oil phase and waste water treatment for the water phase).

The time frame is set to one year in order to investigate different service lives for the base oil variants. These are determined to be 20 weeks for the solvent-raffinate-based cooling lubricant emulsion and 20, twelve and eight weeks for the rapeseed-methyl ester-based cooling lubricant emulsion because of microbial susceptibility.

In order to provide a methodologically identical observation system for both base oil alternatives, it is assumed for the utilisation phase that the cooling lubricant emulsions with both solvent raffinate and rapeseed methyl ester are used in the same way for the same machining process, have the same additive packages and produce the same technological effect. In particular, the additive packages have been overlooked in previous life-cycle assessments.[8] In addition, a study integrating the additive packages into the life-cycle assessment concluded that the different base oils produced the main differences in the results.[9] In addition to the assumptions made, drag-outs of cooling lubricant emulsion due to chip adhesion during the utilisation phase in the amount of 1% of the input quantity are factored.

The determination of a functional unit (FU), i.e. of a quantified benefit of the product system as a comparative unit[10], requires specification of a reference component that is milled within the observation system. A reference component made of steel was selected[11], which has a high complexity of structural

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8 See inter aliaCuevas, P. (2010), p. 39; Ekman, A., Börjesson, P. (2011), p. 298; Vag, C. et al. (2002), p. 44.

9 See Winter, M., Öhlschläger, G. et al. (2012), pp. 311-316.

10 See DIN EN ISO 14044:2006 (2006), p. 11.

11 See Westermann, H.-H., Kafara, M. und Steinhilper, R. (2015), p. 525.

elements (final weight: 4.37 kg, chip removal quantity: 5.05 kg). Identifying further process specifications (including 240 working days, 2-shift system of eight hours each, etc.), this results in a functional unit of 13,000 manufactured reference components per year.

The amount of cooling lubricant emulsion required for the production of this functional unit is provided to the machining process via a single supply system with a filling volume of 450 litres. In addition, the required emulsion quantities are calculated dependent upon the service life. The compositions of the concentrate and base oil quantities are based on literature data: The emulsion is composed of 5% concentrate (consisting of 37% base oil and 63% additives) and 95% water. The overall quantity structure can be found in Table 1.

Table 1: Input and output quantities for the utilisation phase

Service life	Input quantity: CL emulsion (2.6*450 l at 20 wks)		Output quantity: CL used emulsion		Quantity: concentrate (5% of input)	Quantity: base oil (37% of concentrate)
		kg/a		kg/a	kg/a	kg/a
20 weeks for RME and MIN (2.6 bath changes)	Quantity Refillings	1,170	CL disposal (old emulsion at end of service life)	1,170	58.5	21.6
	Additional quantity for chip adhesion	663	CL loss through Chip adhesion	663	33.2	12.3
	Total	**1,833**	**Total**	**1,833**	**91.7**	**33.9**
12 weeks for RME (4.3 bath changes)	Quantity Refillings	1,950	CL disposal (old emulsion at end of service life)	1,950	97.5	36.1
	Additional quantity for chip adhesion	663	CL loss through chip adhesion	663	33.2	12.3
	Total	**2,613**	**Total**	**2,613**	**130.7**	**48.3**
8 weeks for RME (6.5 bath changes)	Quantity Refillings	2,925	CL disposal (old emulsion at end of service life)	2,925	146.3	54.1
	Additional quantity for chip adhesion	663	CL loss through chip adhesion	663	33.2	12.3
	Total	**3,588**	**Total**	**3,588**	**179.4**	**66.4**

CL: Coolants, RME: Rapeseed methyl ester, MIN: Solvent raffinate

With the aid of the life-cycle assessment software Umberto NXT, the determined quantity structure is transferred to a material flow model and the ecological effects of the base oil alternatives solvent raffinate and rapeseed methyl ester are calculated. Datasets from Ecoinvent 3.2 are used for background processes (energy supply, etc.).

The economic assessment from the point of view of the coolant lubricant user includes the procurement costs of the water-miscible coolant concentrates, the water costs for mixing the coolant lubricant emulsion and the disposal fee (gate fee) for the old emulsion charged by the disposal company responsible (Table2).

Table 2: Specific costs for procurement, water, disposal

Cost item	Solvent raffinate	Rapeseed methyl ester
Market price CL concentrate (€/kg)	€4.10/kg	5.68 €/kg
Cost of water consumption (€/t)	1.80 €/t (0.0018 €/kg)	1.80 €/t (0.0018 €/kg)
Disposal costs (€/t)	150 €/t (0.150 €/kg)	150 €/t (0.150 €/kg)

The costs are also related to the functional unit and thus to the quantity structure shown in Table 1. However, the procurement costs of the cooling lubricant concentrates in particular can only reflect a snapshot, since in practice they are dependent on the quantities required, the specific product prices, the supplier contracts and the associated discounts.

The results of the investigations are summarised in Table 3 and represented by a scale system with "++" as the best and "- -" as the worst indicator value.

Table 3: Overall comparison of the criteria for the base oil variants in relation to the functional unit

Indicator	Solvent raffinate	Rapeseed methyl ester with service life		
		20 weeks	12 weeks	8 weeks
Cumulative energy demand	o	++	o	- -
Cumulative raw material demand	++	+	-	- -
Water consumption	++	++	+	o
Land use	++	o	-	- -
CO_2 equivalent	o	++	o	- -
Total cost	++	+	-	- -

For all criteria investigated, the consumption, the emissions and the costs significantly increase with decreasing service life of the emulsion based on rapeseed methyl ester. From a service life of less than 20 weeks, its use is not tenable.

The comparison of the effects of the base oil variants rapeseed methyl ester and solvent raffinate, each with a service life of 20 weeks, results in an ambiguous output from an ecological point of view. While the solvent raffinate's raw material consumption over the entire life cycle is lower, the use of rapeseed methyl ester requires less energy. The water consumption is not significant in either variant, whereas rape cultivation for the production of rapeseed methyl ester makes heavy use of land as a resource. This plays only a minor role in the production, use and disposal of solvent raffinate. By contrast, emissions, expressed as CO_2 equivalents, released in the use of solvent raffinate throughout the life cycle cause a 30% higher environmental impact. In view of this last result in particular, rapeseed methyl ester offers an acceptable alternative with the same service life from an ecological point of view.

From an economic point of view, the use of coolant based on solvent raffinate is recommended for users of cooling lubricant, since the total costs are just under a quarter lower than those of rapeseed methyl ester cooling lubricant. Here again it should be noted that these costs are only a snapshot that cannot reflect supplier contracts, volume discounts or specific prices for speciality products. In any case, the user of cooling lubricant should take a critical look at the stated service life of the cooling lubricant before making a purchase decision and, if necessary, check its impact on cost-effectiveness.

The results generally recommend small and medium-sized metalworking companies to check the use of bio-based water-miscible cooling lubricants available on the market instead of mineral oil-based ones. Particularly for small companies, competent support and experience of their suppliers are required as an additional factor.

1 BACKGROUND AND OBJECTIVE OF THE STUDY

Cooling lubricants (CLs) are of essential importance in metal cutting and forming. They perform the basic functions of lubrication and cooling during tribological contact between the tool and the workpiece, thereby increasing the productivity and cost-effectiveness of industrial metalworking.

Despite innovative approaches such as dry machining and minimum quantity lubrication (MQL), the CL disposal volume and thus CL consumption in the German manufacturing industry rose steadily from 717,000 tonnes in 2011 to 791,000 tonnes in 2014.[12] The quantities disposed of are divided into about 90% water-mixed cooling lubricants and 10% non-water-miscible cooling lubricants (Appendix A). Water-mixed lubricants consist of about 95% water, which is mixed with the CL concentrate before use. If only the CL concentrates are compared with each other, the quantities brought into the domestic market are around 40% water-soluble CL concentrates and 60% non-water-miscible CL concentrates (Appendix A)[13], although in the metalworking industry water-miscible cooling lubricants are used in about 90 % of manufacturing processes.[14]

For companies, CL consumption represents a considerable cost factor, accounting for approx. 8 - 16% of the production costs.[15] Through a series of measures for the storage, care and control of CL, among other things, lubricant use can be cut and tool wear reduced.[16] This increases the efficiency of the use of CLs, reducing waste and cutting costs.

Another way to increase resource efficiency and thus reduce costs is to substitute the CL type with appropriate alternatives. A survey from 1993 showed that about 25% of the water-miscible CL quantities contained mineral-oil-free base oils and about 75% mineral-oil-based base oils.[17] Although it is currently

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12 Our own calculation according to Federal Office of Statistics (2013) – (2016a), Appendix A.

13 Our own calculations according to Federal Office of Economics and Export Control (2015), Appendix A.

14 See Betrieblicher Umweltschutz in Baden-Württemberg (2015a).

15 See Verband Schmierstoff-Industrie e. V. (2016a).

16 See. VDI 3397 Part 2 (2008), p.2.

17 See Baumann, W. and Herberg-Liedtke, B. (1996), p. 26.

known that mineral-oil-based base oils are used as standard for water-miscible cooling lubricants, since 1993 no publicly available figures on the quantity distribution of water-soluble lubricants available on the market or used could be found. In addition, no findings were reached about the ecological and economic effects of the mineral-oil-free base oils of water-miscible CLs and those containing mineral oil along the entire life cycle.

The aim of the study is therefore to research generally available abiotic and biotic base oil alternatives and to review their ecological and economic impacts. The determination of these effects takes place over the entire life cycle of the water-miscible CLs in relation to a defined functional unit and is intended to answer the following questions:

(1) What is the consumption of material, energy, water and possibly land over the life cycle of the CL?

(2) Which supply-critical raw materials are used in the alternatives?

(3) What costs arise for the base oil variants?

The study will serve as a source of information for small and medium-sized enterprises (SMEs) in the metalworking industry and for consultants and research institutions concerning which life-cycle considerations are possible, helpful or even essential in accordance with VDI Guideline 4800 Part 1 and 2 and VDI Guideline 4600 in a decision for or against a CL type, from both an environmental and a cost perspective.

2 STRUCTURE OF THE STUDY

The study is carried out in four stages (Figure 1).

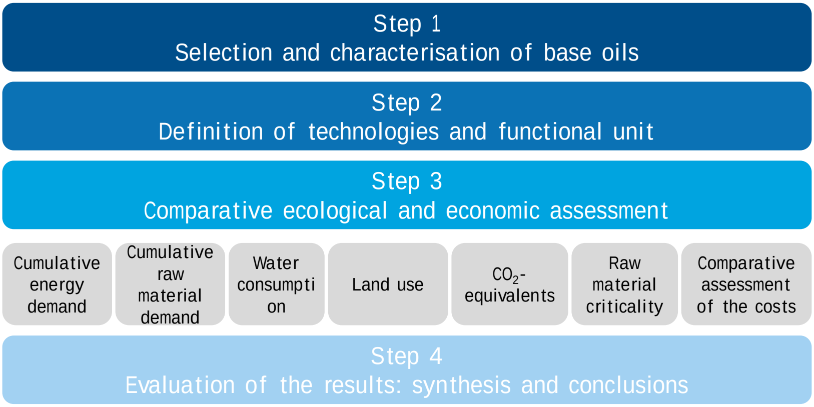

Figure 1: Structure of the study

The first stage involves research into the use of water-miscible CLs in industrial metalworking in Germany. Base oil alternatives for water-miscible cooling lubricants are presented and discussed, and base oil alternatives are established on this basis.

The second stage involves the specification and description of the spatial and temporal investigation framework (process configuration and observation period), the determination of a reference component and the derivation of the functional unit.

In the third stage, a comparative ecological and economic evaluation of the different base oil variants is carried out, considering the following impact categories: cumulative energy demand, cumulative raw material demand, water consumption, land use, emissions in CO_2-equivalents, raw material criticality and costs from the point of view of the CL user.

Finally, in the fourth stage the results are evaluated, the core results summarised and conclusions drawn.

3 SELECTION AND CHARACTERISATION OF BASE OILS

3.1 Use of water-miscible CLs in the metalworking industry

3.1.1 Metalworking processes

Metalworking involves altering the shape and structure of metallic materials through mechanical, physical and chemical processes. The various processes are subdivided into six main groups according to DIN 8589: primary forming, reshaping, cutting, joining, coating and altering material properties.[18] In addition, DIN 51521 provides an overview of water-miscible cooling lubricants which are preferred for use in machining (main group cutting).[19] The machining process is divided into two further areas: machining with geometrically defined cutting edges and machining with geometrically undefinded cutting edges.[20]

There are a variety of different machine tool types available for machining processes. Based on a study by Schischke et al., Figure 2 shows the distribution of installed machine tool types in the EU-27 (as of 2009). Around 63% of the installed machine tools have a geometrically defined cutting edge (lathes and milling machines). Machining processes using geometrically undefined cutting edges (in grinding, honing and lapping machines) are used in 26% of cases.

[18] See DIN 8589-0:2003-09 (2003), p. 7.
[19] See DIN 51521:1999-03 (1999), p. 2.
[20] See DIN 8589-0:2003-09 (2003), p. 8.

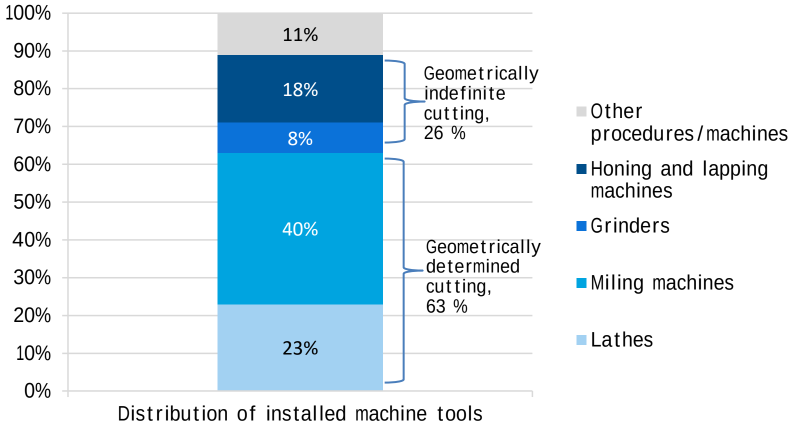

Figure 2: Distribution of installed machine tool types[21]

The focus of the study is on machine tools with a geometrically defined cutting edge (turning and milling processes) in accordance with Figure 2. It should be noted that with these methods, the use of CLs can be reduced in part by minimum quantity lubrication or dry machining.[22]However, according to a survey, these lubrication strategies are applied in only 15% of companies in the metalworking industry[23] and, in addition to the machining process, also depend on the result to be achieved (surface quality, material properties, etc.) and the material to be machined. Overall, the use of flooding lubrication, i.e. the traditional use of CLs, predominates.

For cutting methods with geometrically defined cutting edges, a distinction is made between turning, milling and other methods such as thread cutting and broaching. For the latter processes mainly non-water-miscible CLs are recommended for use, which is why these methods are not considered further.[24] In a comparison of turning and milling processes, milling is carried out in two-thirds of cases. Therefore, the present study focusses on the machining process of milling.

[21] Based on Schischke, K. et al. (2012), pp. 12 et seqq.
[22] See Weinert, K. et al. (2002), p. 67.
[23] See Schröter, M., Lerch, C. and Jäger, A. (2011), p. 14.
[24] See Betrieblicher Umweltschutz in Baden-Württemberg (2015b).

3.1.2 Use of water-miscible CLs

Water-miscible cooling lubricants are used in about 90% of metalworking processes.[25] They perform basic functions of lubrication and cooling during the tribological contact between tool and workpiece and are also used for chip removal and corrosion protection. Water-miscible coolants are composed of a base oil and an additive package and are mixed with water before use. Here a distinction is made between emulsions and solutions, which are described in brief in Table 4.

Table 4: Description of water-miscible CLs[26]

	CL emulsions	CL solutions
Base oils	• Mineral oils • Synthetic • Ester/(vegetable oils)	• Water-soluble org. substances (e.g. polyalkylene glycols)
Common additives	• Emulsifiers • Corrosion inhibitors • Solubilisers • Anti-foaming agents • Microbicides • Polar agents and extreme pressure additives • Pigments	• Corrosion inhibitors (inorganic salts) • Wetting agents (detergents) • Water-soluble org. substances
Characterisitics	• Dispersive distribution of one liquid in another • Distribution is strongly influenced by interfacial tension between molecules of the two liquids • Surface tension is reduced by emulsifiers, resulting in a stable emulsion	• Homogeneous mixture of inorganic and organic substances with water • No emulsifiers are needed because there is equal interfacial tension in the liquids to be mixed

The choice of water-miscible CLs depends in particular on the type and composition of the material, in combination with the machining process used. The literature gives recommendations for the selection of water-miscible cooling lubricants depending on the material and the machining process (Table 5).

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[25] See Betrieblicher Umweltschutz in Baden-Württemberg (2015c).

[26] See Betrieblicher Umweltschutz in Baden-Württemberg (2015d); Kassack, J. F. (1994), p. 8; based on Möller, U. J. and Nasser, J. (2013), p. 568.

Table 5: Recommendations for the selection of water-miscible cooling lubricants depending on the material and the machining process[27] [28]

Material	Milling		Turning		
	BUBW	Gomeringer, R. et al.	BUBW	Gomeringer, R. et al.	
				Roughing	Smoothing
Casting	Emulsion	Emulsion*	Emulsion	-	Emulsion
Steel	Emulsion	Emulsion Solution	Emulsion	Emulsion Solution	Emulsion
VA-steel	Emulsion	n.a.	Emulsion	n.a.	n.a.
Magnesium	N/S	-	N/S	-	-
Copper	N/S	Emulsion*	N/S	-	Emulsion*

BUBW = Betrieblicher Umweltschutz Baden-Württemberg; N/S = not specified; *if dry processing is not possible; - = use of water-miscible CLs not recommended

The use of CLs emulsions for turning and milling of cast iron and steel is recommended in most cases. CL solutions play a minor role here. For the remaining materials, either information is missing or the use of CL emulsions or CL solutions is generally not appropriate. In these cases, non-water-miscible CLs should usually be used.

3.2 Based on recommendations drawn from the literature, the present study deals with steel as a material and a CL emulsion as CL type. Base oils for CL emulsions

A large number of different oils and substances (e.g. fats, polymers, salts) can be used to produce CL emulsions (Figure 3).

[27] Based on Betrieblicher Umweltschutz in Baden-Württemberg (2015e).

[28] Based on Gomeringer, R. et al. (2014), p. 308.

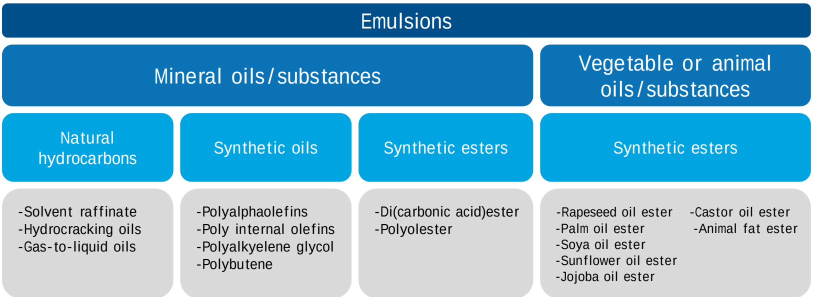

Figure 3: Potential oils and substances for the production of CL emulsions[29]

In principle, a distinction is made between substances and oils of mineral origin (abiotic) and substances and oils of plant or animal origin (biotic). The corresponding production methods are described in detail in the literature.[30]

3.2.1 Mineral base oils

The agreed view of the experts interviewed is that the use of mineral-oil-based base oils is significantly better than animal and vegetable oils and substances. According to the official mineral oil data of the BAFA, about 21,100 tonnes (domestic deliveries) of water-miscible mineral-oil-based cooling lubricants were used in 2015 (Appendix A). [31]

As shown in Figure 3, the mineral oils and substances differ in natural hydrocarbons (in particular solvent raffinates (MIN)), synthetic oils produced by chemical processes (in particular polyalphaolefins) and in synthetic esters (in particular dicarboxylic acid esters).

Conventional mineral oils (solvent raffinates) are produced by distillation and refining of crude oil[32]. They make up the majority of the base oils used and are usually used for regular, i.e. no demanding, applications.[33] These include, for example, the water-miscible cooling lubricants.

[29] Based on Brinksmeier, E. et al. (2015), p. 621.

[30] See Möller, U. J. and Nassar, J. (2013), pp. 83 ff.; Mortier, R. M.; Fox, M. F. and Orszulik, S. T. (2010), pp. 35 ff.; Mang, T. (1983), p. 41; Mang, T. and Dresel, W. (2007), pp. 63 et seqq.

[31] See Federal Office of Economics and Export Control (2015).

[32] See Möller, U. J. and Nassar, J. (2013), p. 70; Verband Schmierstoff-Industrie e. V. (2016b).

[33] See Verband Schmierstoff-Industrie e. V. (2016b).

The synthetic base oils are produced from chemically defined basic building blocks, which include mineral oil, and often perform special tasks.[34] Polyalphaolefins are used, for example, for high-performance cooling lubricants and are characterised by minimal evaporation, a high flash point at low viscosity, a high viscosity index and excellent shear and aging stability.[35] A survey of experts in this study (Appendix B) showed that polyalphaolefins are primarily used for specific user requirements, such as cases where high forces are generated or for long service lives. They continue to be used primarily in the grinding industry[36] when particularly low evaporation losses at the processing point are required.[37] Polyalphaolefins have better a emissions behaviour - with the same viscosity of 10-30 Ns/m^2 - than solvent raffinate. This may, under certain circumstances, be critical for compliance with emission limit values or may lead to a reduction in drag-outs. However, the use of polyalphaolefins as a base oil is usually standard practice only for non-water-miscible CLs[38], as they do not emulsify well and have a higher procurement cost compared to solvent raffinate as a result of the synthesis process.

Dicarboxylic acid esters can be used as synthetic esters for lubricants. They are characterised by a high biodegradability and low volatility. A significant disadvantage of dicarboxylic acid esters and other synthetic esters compared to polyalphaolefins and solvent raffinate lies in the poor solubility of additives and, above all, in the high procurement costs.[39] Nevertheless, there are also current developments in this product area that will make water-miscible cooling lubricants suitable for practical application in the future.[40]

For the ecological and economic assessment of this study, solvent raffinate is chosen as a base oil suitable for practice for the reasons mentioned above.

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[34] See Möller, U.J. and Nassar, J. (2013), p. 84.
[35] See Rehbein, W. (2016).
[36] See telephone interview, 01.07.2016, Appendix B.
[37] See telephone interview, 04.07.2016, Appendix B.
[38] See telephone interview, 04.07.2016, Appendix B.
[39] See Möller, UJ and Nassar, J. (2013), p. 91; Bartz, W.; Moller, U. (2000), p. 760.
[40] See Oemeta Chemische Werke GmbH(2016).

3.2.2 Animal and vegetable base oils

According to the information provided by the experts surveyed, the use of animal base oils for the production of emulsions is very rare (Appendix B). Possible base oil sources here are tallow fatty acids and lard oils. Animal base oil alternatives have limited acceptance among users due to the BSE crisis and the dioxin scandal. Furthermore, there are religious restrictions, as a 'kosher' or 'Halal' certification of CLs based on animal substances and oils is relatively expensive. Animal substances and oils are preferable for use as additives, if at all.

Biolubricants or bio-based lubricants should comply with the following minimum requirements, in accordance with the Technical Report CEN/TR 16227 of the European Committee for Standardization (CEN):[41]

- **Renewability**: Content of renewable raw materials is at least 25%.
- **Biodegradability**: ≥ 60% according to OECD 301 for oils (≥ 50% for greases).
- **Toxicity**: not to be labelled as "environmentally hazardous" according to CLP Directive 1272/2008/EC.
- **Performance**: “usability". Both the lubricant manufacturer and the consumer of the product must ensure that the recommended lubricant is suitable for a particular application.

Biobased CLs as a division of biolubricants can have properties that make them more advantageous for special production steps than mineral-oil-based CLs. These include a better lubricity, a higher flash point, better evaporation properties and higher skin compatibility.[42] The proportion of bio-based metalworking oils (including water-miscible and non-water-miscible CLs) in the overall metalworking oils market is currently around 9.2%.[43]

[41] See DIN CEN/TR 16227 (DIN SPEC 51523):2011-10 (2011), p. 12.
[42] See Effizienz-Agentur NRW (2008), p. 22.
[43] See Fachagentur Nachwachsende Rohstoffe e. V. (2014a); p. 32.

Bio-based CLs are produced on the basis of, for example, rapeseed oil or soybean oil, whereby the Fachagentur Nachwachsende Rohstoffe (FNR) association notes that "water-miscible CLs are not considered biogenic" [44]. The Betrieblicher Umweltschutz in Baden-Württemberg (BUBW) portal points out that emulsions based on biodegradable products tend to be more susceptible to microorganisms, have shorter lifetimes and thus require more biocide for preservation.[45] Nevertheless, water-miscible CLs are available on the market which have been produced on the basis of renewable raw materials and are used in transesterified form.[46] In addition, various manufacturers and associations/authorities conducted a survey of experts who are active in the field of CLs and know the market situation. Four experts contacted on this topic confirmed the use of plant-based water-miscible CLs as a niche product and named rapeseed methyl ester (RME) as a base oil variant, yet added that it has a low aging stability, is oxidatively unstable and is highly susceptible to hydrolysis in practical application. Alternatively, esters based on palm oil and coconut oil have been mentioned, but for economic reasons are more likely to be used abroad or as high-quality additives.

The topic of biolubricants, including the use of bio-based, water-miscible cooling lubricants, has also been discussed[47] in previous and current symposia[48]. This underlines a growing interest in and relevance of the sector. The research on the successful use of bio-based (water-miscible) cooling lubricants is still relatively young compared to the use of mineral oil (water-miscible) lubricants, so that innovations in the future will further develop the technical properties of, for example, water-miscible water-based lubricants based on rapeseed oil.[49]

In the context of resource efficiency, rapeseed methyl ester is used as another base oil for the study. Bio-based, water-miscible CLs are available on the market. Nevertheless, their composition is subject to company secrecy.

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[44] Fachagentur Nachwachsende Rohstoffe e. V. (2014b), p. 467.

[45] See Betrieblicher Umweltschutz in Baden-Württemberg (2015a).

[46] See Riedel Schmierstoffe (2016) and Wascut Industrieöle GmbH (2001).

[47] See Hessen-Biotech (2016); Fachagentur Nachwachsende Rohstoffe e. V. (2016); Fachagentur Nachwachsende Rohstoffe e. V. (2014a).

[48] See Fachagentur Nachwachsende Rohstoffe e. V. (2014a); pp. 218 – 224.

[49] See Wascut Industrieöle GmbH (2001).

Rapeseed oil often provides the foundation for applications in the field of bio-based water-miscible CLs. The LCA data that can be researched for rapeseed methyl esters has therefore been chosen as the representative base oil for bio-based, water-miscible CLs.

3.3 Research on life-cycle assessments to compare different base oil variants

In recent years, various life-cycle assessments about lubricants have been prepared, with the aim of comparing different base oil variants with each other. In the course of a literature search, the base oils investigated, the life phases, the chosen functional unit and the impact categories analysed in these studies were surveyed. This serves as a basis for aligning the assumptions and limitations to be made in the current study with standard practice in the literature (Table 6).

Table 6: Life-cycle assessments on the use of lubricants

Base oils examined	Life phase examined	Functional unit	Impact category	Source
Mineral oil, rapeseed oil and synth. ester as lubricant base oil	Preliminary raw material chain, Manufacturing phase, Utilisation phase (Loss of lubrication)	1 m^3 Hydraulic oil	GWP, AP	Vag, C.; Marby, A. et al. (2002)
Mineral oil and rapeseed oil as hydraulic oil	Preliminary raw material chain, Manufacturing phase, Utilisation phase	1 kg base oil or production of the machine	GHG, AP, ODP, EP, HM, pesticides, solid waste, energy demand, summer/winter smog	McMannus, M.; Hammond, G. et al. (2004)
Mineral oil, rapeseed oil, palm oil, animal fat and used cooking oil as nwmb CLs	Preliminary raw material chain, Manufacturing phase, Utilisation phase, End-of-life	1000 machined workpieces	GWP, AP, NP, CED, POCP, PM, RD, CRP	Dettmer, T. (2006)
Mineral oil and soybean oil as metalworking oil	Preliminary raw material chain, Manufacturing phase, Utilisation phase, End-of-life	Surface (m^2) rolled aluminium	GWP, AP, EP, POCP, CRP, fossil energy	Miller S.; Landis, A. et al. (2007)
Mineral oil, rapeseed oil and soybean oil as lubricant base oil	Preliminary raw material chain, Manufacturing phase	1 kg Lubricant	GWP, AP, CRP, EP, ODP, POCP, PM Ecotoxicity	Cuevas, P. (2010)
Mineral oil and rapeseed oil as lubricant base oil	Preliminary raw material chain, Manufacturing phase, End-of-life	1 l base oil for hydraulic oils	GWP, EP, AP, POCP, primary energy, biodegradability	Ekmann, A.; Börjesson, P. (2011)
Mineral oil and jatropha oil as wmb CLs	Preliminary raw material chain, Manufacturing phase, Utilisation phase, End-of-life	500 kg machined material	ADP, GWP, Eco Indicator 99	Winter, M.; Öhlschläger, G. et al. (2012))

ADP = abiotic resource consumption; AP = acidification potential; CRP = carcinogenic risk potential;
EP = eutrophication potential; GHG = greenhouse gas; GWP = global warming potential; HM = heavy metals;
CED = cumulative energy demand; NP = nutrient enrichment potential; nwmb = not water-miscible;
ODP = ozone depletion; PM = particulate matter pollution potential; POCP = photochemical ozone creation potential; RD = resource demand;
wmb = water-miscible

A comparison of the life-cycle assessments shows that all investigations consider mineral oil and five out of seven investigations look at rapeseed oil as a base oil variant. The focus on mineral oil and rapeseed oil as relevant base oil variants corresponds with the results of the selection process for the present study.

The base oils under consideration were, however, used in different ways, as hydraulic oils, forming oils or non-water-miscible and water-miscible CLs. Although different types of lubricants are analysed in the studies, they can still be used to compare the LCA methodology.

With respect to the preparation or formulation of the lubricants, additives were not considered or neglected in six out of seven studies. This limitation was justified by the fact that additives account for only a small proportion of the lubricant[50], there are too many different additives[51], the recipes are kept secret by the lubricant manufacturers[52] or it is assumed that the same type and amount of additives is used in the lubricants[53]. Only Winter et al. have taken into account the additives of the lubricants in a study, concluding that the respective base oils account for the main difference in the LCA results.[54] In the present study, therefore, there is no consideration of the additive packages.

All investigations take into account the phases of life, the preliminary raw material supply chain and the manufacturing phase. By contrast, the utilisation phase and the end-of-life phase are neglected in some studies. The aim of the present study is to analyse the environmental consumption throughout the life cycle, so that all lifecycle phases are included in the assessment.

Furthermore, a comparison of the functional units shows that in four of the seven studies considered, the supply of 1 kg, 1 m^3 or 1 l of the respective base oil or lubricant is taken into account. Dettmer (2006), Miller et al. (2007) and Winter et al. (2012), on the other hand, relate the functional unit to the utility of the lubricant and compare base oil alternatives based on a specific number of products produced using the lubricant. In the present study, the functional unit is also based on a benefit, for example the production of a

[50] See Cuevas, P. (2010), p. 39; Ekman, A. and Börjesson, P. (2011), p. 298.
[51] See Cuevas, P. (2010), p. 39.
[52] See Dettmer, T. (2006), p. 156.
[53] See Vag, C. et al. (2002), p. 44, Miller, S. et al. (2007), p. 4144.
[54] See Winter et al. (2012), p. 315.

certain amount of goods, in order to consider fully the entire system including all process specifications that vary with the use of different base oil alternatives (e.g. different lifetimes of the CL emulsions).

Nearly every study examines the global warming potential in the impact category climate change, which is also determined in the present study. The consideration of other impact categories differs, significantly in some cases, between the investigations. The present study is based on the VDI Guidelines 4800 Part 1 and 2 and 4600 and examines, among other things, the cumulative raw material demand (CRMD) and the cumulative energy demand (CED), which was also examined by Dettmer (2006), for example.

4 METHODOLOGY FOR ECOLOGICAL AND ECONOMIC ASSESSMENT

4.1 Spatial definition of the investigation framework

The framework of the investigation determines the system boundaries within which the base oil variants are investigated and evaluated. An integrated ecological and economic assessment requires an observation of the entire life cycle, i.e. “from the cradle to the grave" (Figure 4).

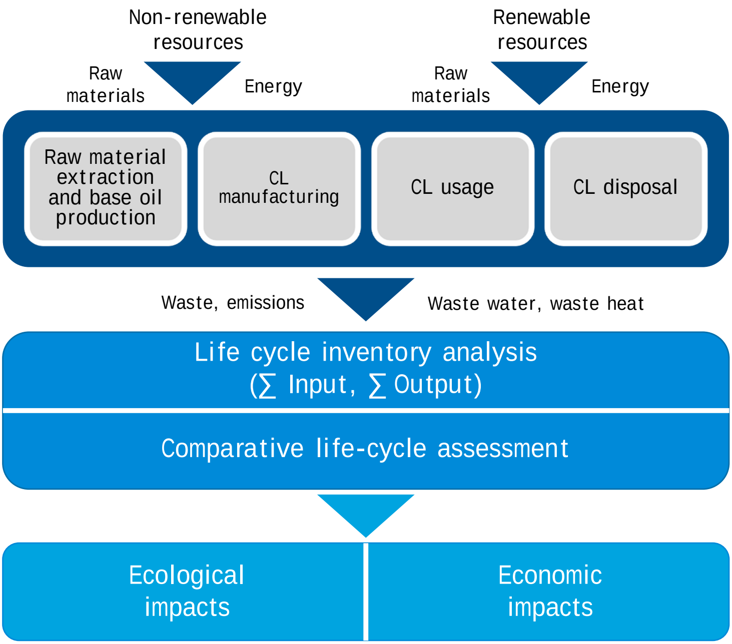

Figure 4: Framework of investigation for holistic ecological and economic assessment of base oil alternatives for cooling lubricants[55]

For each of the four phases of life, the data is recorded for all necessary input-side (raw materials, energy, etc.) and output-side (waste, emissions, etc.) energy and material flows and compared by means of a life cycle inventory analysis. Based on this data, a comparative assessment of the ecological and economic effects of the base oil variants is carried out.

[55] Based on Dettmer, T. (2006), p. 100.

4.1.1 Raw material extraction and base oil production

The system boundaries of raw material extraction and base oil production for the mineral-oil-based base oil solvent raffinate and for the mineral-oil-free base oil rapeseed methyl ester each comprise three main steps: provision (step 1), processing (step 2) and final production or transesterification (step 3) (Figure 5).

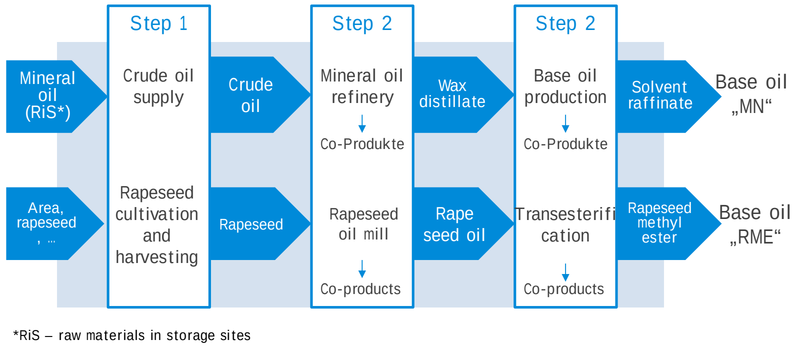

Figure 5: Material flow diagram for base oil production

The two variants have in common the fact that the individual process steps mainly involve joint processes, in which co-products are generated in addition to the main product, creating an additional benefit for the system under consideration. Since a system extension is not expedient here, the process consumption (input and output flows) between the main product and the co-products must be split according to allocation rules. The determination of the proportion allocated to the individual co-products is based on allocation factors. These may be based on physical or economic parameters and reflect the actual benefits of all co-products.[56]

The system limits for the base oil production of solvent raffinate include the distillation and fractionation of crude oil in the oil refinery as well as the

[56] See VDI 4800, Part 1 (2016), p. 15.

further extraction of the resulting wax distillate and subsequent hydrogenation processes. Therefor the present study uses mass-based allocation factors for the joint processes (Figure 12).[57]

For the production of base oil from rapeseed oil, all steps to extract raw materials are taken into account: from soil cultivation, sowing, fertilisation, crop protection measures and rapeseed harvesting through to transport to the oil mill. In the subsequent production of base oil, the rapeseed is further processed in the oil mill to make rapeseed oil and rapeseed meal, followed by the transesterification of the rapeseed oil with the corresponding alcohols to form rapeseed oil esters and glycerol.[58] It is assumed that cultivation, oil extraction and transesterification take place in Germany. Since the rapeseed meal produced is significantly above the amount of oil produced but has a lower economic value in its use (e.g. as cattle feed), the main and co-products of the production of the base oil are allocated using economic parameters (Figure 13). The allocation factors used are based on statistical market prices from 2004, as specified in the current inventory database Ecoinvent 3.2.[59]

4.1.2 CL manufacturing

A water-miscible CL concentrate is produced by formulating the base oil and additives, which determines the performance characteristics of the CLs. In most cases, this production takes place in batches as part of a technical production process, while maintaining specific temperatures and stirring processes.[60]

Within the framework of this phase of life, it is assumed that the production steps for producing the CL concentrate are the same for the base oils solvent raffinate and rapeseed methyl ester under consideration. Furthermore, it is assumed that the same additive packages are used with the same production processes for both base oil variants; based on the same input and output streams, the life phase of cooling lubricant production is negligible or requires no further consideration in the life cycle inventory. This assumption

[57] See Kolshorn, K.-U. and Fehrenbach, H. (2000), pp. A-47ff.; Fehrenbach, H. (2005), pp. 24, 26.
[58] See Ecoinvent 3.2 (2015).
[59] See Ecoinvent 3.2 (2015).
[60] See Hansen, A., Hallmann, C. and Schmehl, M. (2005), p.19.

was also made on the basis of other studies on comparative life-cycle assessments of lubricants (section 3.3).

4.1.3 CL usage

The phase of CL utilisation considers the use of CLs during material processing and the resulting effects. The assessment is based on the assumption that both base oils are used in the same way for the same treatment process and produce the same technological effect.

The framework of investigation for the machining process is defined according to Figure 6 and consists of three main process components: Machine tool, CL extraction and CL filtration and supply, which also includes chip de-oiling. In practice, a washing process may follow, but it is not mandatory and will not be considered in this study.

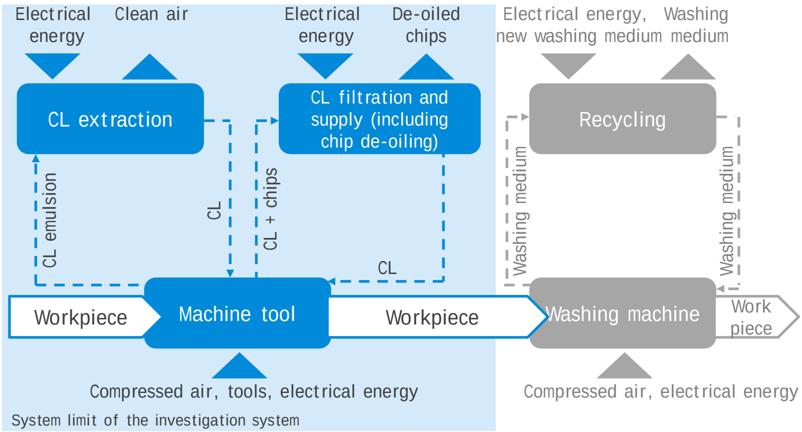

Figure 6: System boundary for the machining process under consideration[61]

Although the CLs is circulated within the machining process, it can also be removed from the circulatory system via chip and workpiece adhesions, leaks or evaporation. These drag-outs can be specifically reduced by means

[61] Based on Madanchi, N. et al. (2015), p. 363.

of technical measures such as chip de-oiling (1), workpiece cleaning (2), suction (3), filtration and feed (4), CL maintenance and tool life management (5). They are considered as follows for the present study:

(1) Chip de-oiling

Chip de-oiling via pressing, centrifuging or briquetting of the chips. The residual oil content of the chips after pressing is less than 1% [62], after centrifuging or briquetting it amounts to about 1%[63]. Depending on the de-oiling process, the recovered CL quantities can be returned to the circulation system (CL supply).[64]

To map a resource efficient system, it is therefore assumed that the chips are de-oiled before disposal. Within the use case, a residual oil content of 1% of the chips is assumed, while the remaining CL quantities are returned to the system.

(2) Workpiece cleaning by compressed air

Another type of drag-out is caused by adhesion of the CL to the workpieces. With a view to resource-efficient use, workpieces wetted with CL are often blown off with compressed air. This cleaning is also carried out because clean or cool lubricant-free workpieces are usually needed in subsequent processes within the process chain. For safety reasons it is advisable to blow off the workpiece wetted with CL with compressed air in a housed machine, so that no emissions are inhaled by the workers.[65] In the following, it is assumed that the CL thus remains in the system and has no influence on the life cycle inventory balance within the machining process under consideration.

(3) CL extraction

In the case of CL extraction, a decentralised single-station extraction with constant extraction volume flow is assumed, since these tend to be used

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[62] See Liedtke, S. (1999), p. 124 et seq.

[63] See Mayfran (2015), p. 2.

[64] See Liedtke, S. (1999), p. 124 et seq.

[65] See Deutsche Gesetzliche Unfallversicherung e.V. (2011), p. 38.

more often in SMEs than central systems because of lower investment costs and more flexible use. The demand for electrical energy for the system is constant based on the constant extraction volume flow; it is assumed that the cooling lubricant is returned to the milling process without losses. Single-station extraction therefore has no effect on the CL flow.

(4) CL filtration and supply

The aim of CL filtration and supply is the circulation of the CL via the machine tool. In the present use case, a decentralised individual supply with uncontrolled feed pumps is assumed (milling machining centre with connected cooling lubricant processing plant). This arrangement is useful when a small number of machine tools are installed, and is often used in smaller companies.[66] It is further assumed that the CL variants under investigation show similar physical properties due to their high water content (e.g. viscosity at 20 °C approx. 1 mm^2/s, density at 20 °C approx. 1 g/cm^3) and the same pumping power is used. In addition, a closed tank is assumed so that CL evaporations condense on the encapsulation. CL filtration and supply therefore has no accounting impact on the valuation.

(5) Maintenance measures for service life management

CLs are inevitably subject to constant aging during operation. Due to many factors, such as temperature, pressure, entry of atmospheric oxygen and impurities, aging reactions such as polymerisation, oxidation, hydrolysis and cracking are triggered, which reduce the performance of the CLs.

Maintenance measures significantly influence the length of the utilisation phase for CLs. Thus, the service life of an emulsion in a single machine can be increased from four to 20 weeks depending on maintenance procedures (Figure 7).[67]

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[66] See Dopatka, J., Obst, M. and Siegfried, F. (1993), p.18.
[67] See Kiechle, A. (1996), p. 8.

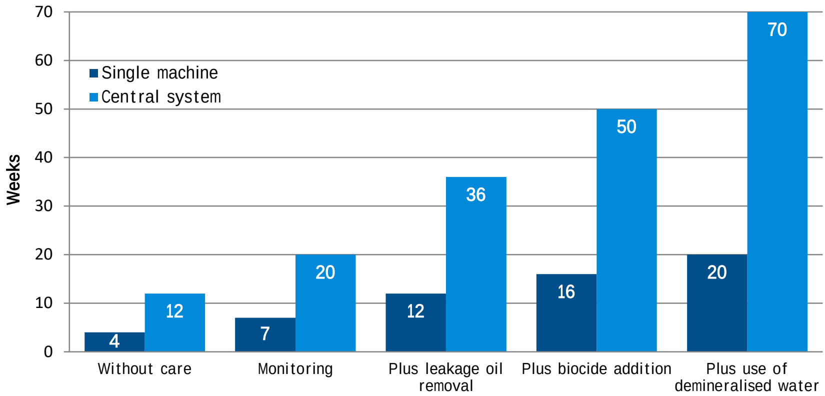

Figure 7: Emulsion life in single machine and central system[68]

From an ecological and economic point of view, it makes sense to maximise the service life of the cooling lubricant. It is therefore assumed that the CL emulsion will be maintained in the machining process under consideration and reach a service life of 20 weeks. This corresponds to 2.6 changes of the CL emulsion in a year and is due to infestation with microorganisms, which affects the service life and is largely independent of the actual machine utilisation. The service life of 20 weeks is set for both base oils, solvent raffinate and rapeseed methyl ester.

In addition, it has to be considered that the CL emulsion based on rapeseed methyl ester tends to be susceptible to hydrolysis, microbial infestation and gumming, which sometimes has a negative effect on service life.[69] McManus et al. compare the use of rapeseed oil and mineral-oil-based hydraulic oils and point out the higher sensitivity of the rapeseed oil variant in terms of pressure and temperature, as well as its corrosive properties compared to the hydraulic components. With regard to service life, it was found that, on the one hand, the same service lives resulted, on the other hand, that bath changes were 1.5, 2 and 3 times more frequent.[70] McManus et al. therefore

[68] See Kiechle, A. (1996), p. 8.
[69] See Fachagentur Nachwachsende Rohstoffe e. V. (2012), pp. 8 – 10.
[70] See McManus, M., Hammond, G. and Burrows, C. (2004), pp. 170 – 172.

assume an average of a double service life for mineral-oil-based CL compared to rapeseed-oil-based CL.

Based on this discussion, an equal service life (20 weeks) of the mineral-oil and rapeseed-oil-based CL emulsion and a shorter service life for the rapeseed-methyl-ester-based CL emulsion is assumed in the present study. The shorter service lives are set at twelve and eight weeks.

4.1.4 CL disposal

As far as disposal is concerned, on the one hand the amounts of used CL emulsion that come about at the end of the service life, i.e. on each bath change, must be considered, and on the other hand, the chip adhesions which have a residual moisture content of 1% (section 4.1.3). For the used CL emulsion it is assumed that an external splitting system is used for treatment, which mainly uses vacuum evaporation or ultrafiltration[71] and separates the cooling lubricant into an oil-containing phase and a water phase. An in-company emulsion splitting system is usually economically viable only from a waste volume of more than 100 cubic metres per year. However, it is advisable to check whether additional aqueous process wastes are generated or to be reprocessed for in-house treatment.

The aqueous phase is treated after the emulsion splitting by a waste water treatment, while the waste oil phase is thermally recycled (Figure 8).

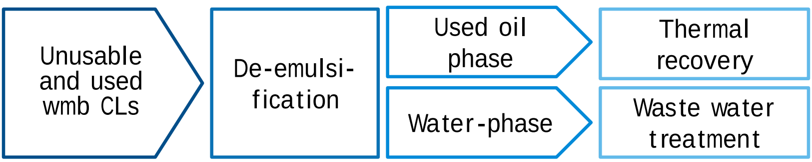

Figure 8: Disposal routes for cooling lubricants[72]

For chip adhesions, a chip fusion system is assumed during which the CL is burnt. Since the amount of drag-out due to chip adhesions is the same for all CL variants considered, these are not taken into account in the analysis.

[71] See VDI 3397 Blatt 3 (2008).

[72] See VDI 3397 Blatt 3 (2008).

4.2 Definition of the reference component

In chapter 3 it was pointed out that a majority of about 63% of machining processes are carried out with a geometrically defined cutting edge, whereby milling operations are the most frequent. Furthermore, CL emulsions are mostly recommended for processing steel in these machining processes. On the basis of these parameters, a reference component is to be selected which is produced by a milling process and reflects the associated machining operations with the most common structural design elements, such as grooves or holes of different dimensions.

By means of a literature review, it was possible to determine three reference components which correspond to the requirements of such a milling process. All three reference components were originally designed to evaluate and compare the energy efficiency of various machine tools during the manufacture of a component.

Figure 9 shows the three reference components (marked A, B and C).

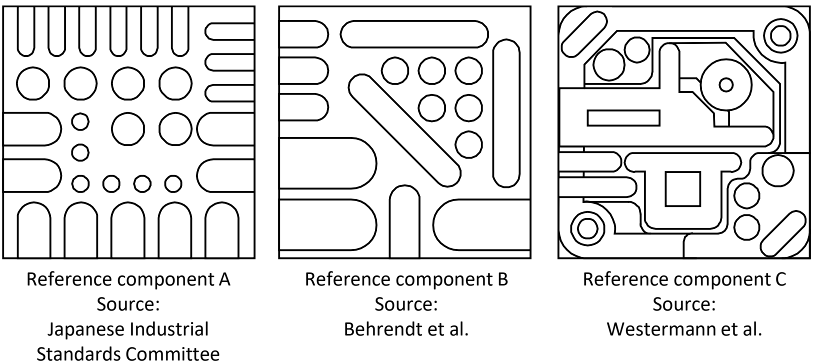

Figure 9: Comparison of possible reference components[73]

The reference component A of the Japan Machine Tool Builders' Association (JMTBA) comprises two different structural elements (bores and open grooves/pockets), which are manufactured in different designs (radii, depths

[73] Japanese Industrial Standards Committee (2010), pp. 1 ff.; Behrendt, T., Zein, A. and Min, S. (2012), p. 44; based on Westermann, H.-H., Kafara, M. and Steinhilper, R. (2015), p. 525.

and lengths). Following the JMTBA, Behrendt et al. designed a similar reference that also has closed longitudinal grooves. The reference component C of Westermann et al. consists of a variety of different structural elements, including holes, open and closed pockets and contours. This reference component was calculated on the basis of more than a thousand real components. [74]

A comparison of the reference components shows that the version by Westermann et al. has the highest complexity of constructive elements used. In order to meet the changing requirements of industrial production, the reference component of Westermann et al. is used.

This is shown in Figure 10 and is milled from a steel blank with a length and width of 200 mm and a height of 30 mm. One component is produced per 15 minutes or a chip quantity of 5.05 kg is removed, so that the final weight of the component is 4.37 kg.

[74] See Westermann, H.-H, Kafara, M. and Steinhilper, R. (2015), p. 524.

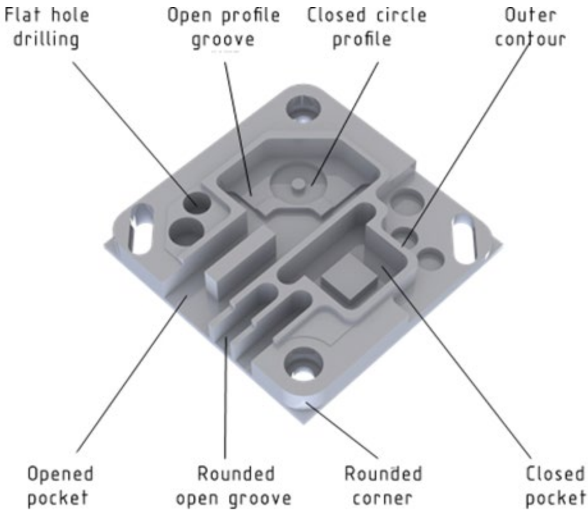

Figure 10: Selected reference component of Westermann et al.[75]

Based on the study by Westermann et al., the steel material with the designation C60E or 1.1221 is considered, which is easily machinable. This material was selected on the basis of tensile strength (about 750 to 1,000 N/cm^2). The basis for this was the analysis of the tensile strength of the aforementioned thousand real workpieces and the calculation of the mean value for all tensile strengths. This analysis showed that the material C60E, in particular, is a representative average of all values.[76]

4.3 Definition of the functional unit

The term functional unit is defined according to DIN EN ISO 14044 as the quantified performance of a product system for use as a reference unit.[77] In accordance with the determination of further boundary conditions for the milling process (including 240 working days, two-shift system of eight hours each etc., Table 7), a functional unit is calculated for the present observation

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[75] Based on Westermann, H.-H.; see Kafara, M. and Steinhilper, R. (2015), p. 525.

[76] See Westermann, H.-H; Kafara, M. and Steinhilper, R. (2015), p. 524.

[77] See DIN EN ISO 14044:2006 (2006), p. 11.

system, i.e. a quantified performance of 13,000 manufactured reference components per year or a generated chip quantity of approx. 65,650 kg (Table 7).

Table 7: Derivation of the functional unit

Description	Unit	Value	
Shifts a day	-	2.00	Fixed boundary conditions
Shift duration	h	8.00	
Working days per year	Days	240	
Total number of operating hours	h/year	3,840	
Capacity utilisation	%	85.00	
Productive machine time	h/year	3,264	
Production time per component	h/pc	0.25	
Chip quantity per component	kg/pc	5.05	
Components produced	**Pcs/year**	**13,000**	Functional unit
Chip quantity per year	**kg/year**	**65,650**	

The production volume of 13,000 units is calculated on the assumption that the reference components are manufactured in a processing time of 15 minutes per component and with a machine availability of 85 % on 240 working days, each with two eight-hour shifts.

The functional unit is created in the utilisation phase, and is structured as shown in the full material flow diagram of the use case below (Figure 11). The material flow diagram is identical for both CL base oil alternatives, solvent raffinate and rapeseed methyl ester.

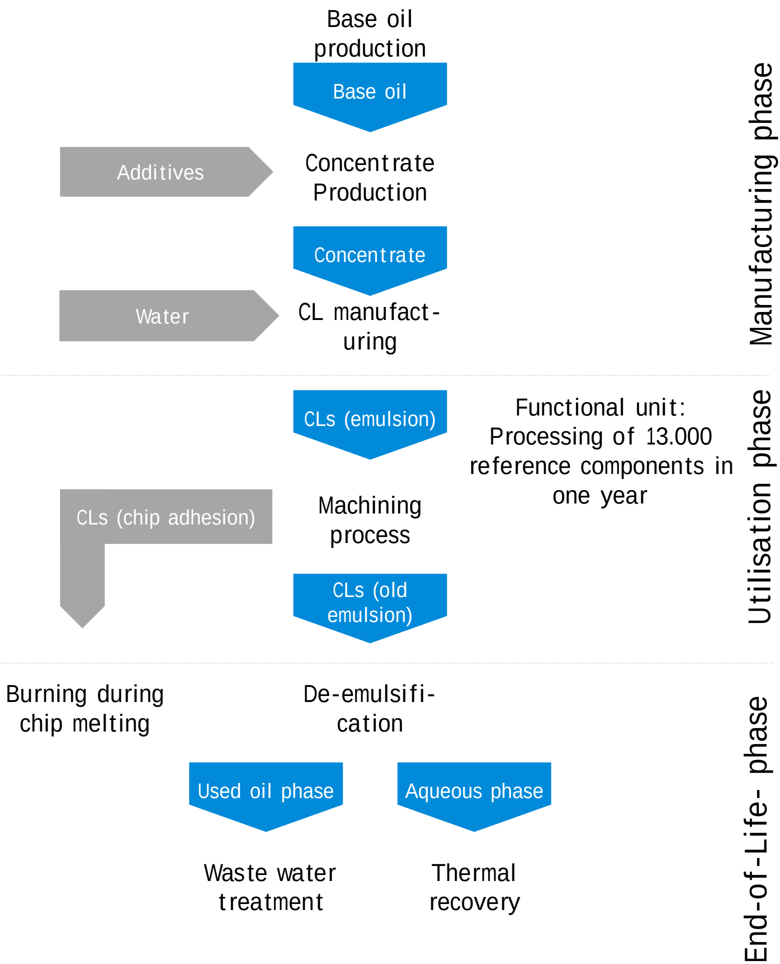


Figure 11: Material flow diagram for the entire CL lifecycle

4.4 Ecological assessment: Quantification of boundary parameters and input and output streams

To perform the milling operation, a specific amount of CL emulsion is required within the one-year observation period to produce the specified functional unit of 13,000 components. The same composition of both CL emulsions is assumed (section 4.1.3). This is based on data from literature[78] and practice[79], defined as follows:

$$100\%\ CLs_{Emulsion} = 5\%\ CLs_{concentrate} + 95\%\ water$$

$$100\%\ CLs_{concentrate} = 37\%\ base\ oil + 63\%\ additives$$

The resulting quantities of required CL concentrate and base oil for the production of the functional unit (13,000 components) are calculated using the CL composition and the required quantities of CL emulsion. These are calculated using the filling volume of the individual supply system and the service life and loss amount of the emulsion during this period (Table 8). A typical filling volume of a single plant for the described milling process is 450 litres. The service life is determined for the CL emulsions with solvent raffinate and rapeseed methyl ester, as described in section 4.1.3, at 20 weeks. In addition, reduced service lives of twelve and eight weeks for the CL emulsions based on rapeseed methyl ester are considered. As explained in section 4.1.3, the CL losses are limited to the drag-out quantities due to residual CL adhesion on the chip (residual moisture 1%) and remain constant for the different service lives.

[78] See Baumann, W. and Herberg-Liedtke, B. (1996), p. 48; Mang, T. and Dresel, W. (2007), p. 412.
[79] See FUCHS Schmierstoffe GmbH (2013) and Carl Bechem GmbH (2015).

Table 8: Input and output quantities for the utilisation phase

Service life	Input quantity: CL emulsion (2.6*450 l at 20 wks)		Output quantity: Used CL emulsion		Quantity: concentrate (5% of input)	Quantity: base oil (37% of concentrate)
20 weeks for RME and MIN (2.6 bath changes)		kg/a		kg/a	kg/a	kg/a
	Quantity Refillings	1,170	CL disposal (old emulsion at end of service life)	1,170	58.5	21.6
	Additional quantity for chip adhesion	663	CL loss through chip adhesion	663	33.2	12.3
	Total	**1,833**	**Total**	**1,833**	**91.7**	**33.9**
12 weeks for RME (4.3 bath changes)		kg/a		kg/a	kg/a	kg/a
	Quantity Refillings	1,950	CL disposal (old emulsion at end of service life)	1,950	97.5	36.1
	Additional quantity for chip adhesion	663	CL loss through chip adhesion	663	33.2	12.3
	Total	**2,613**	**Total**	**2,613**	**130.7**	**48.3**
8 weeks for RME (6.5 bath changes)		kg/a		kg/a	kg/a	kg/a
	Quantity Refillings	2,925	CL disposal (old emulsion at end of service life)	2,925	146.3	54.1
	Additional quantity for chip adhesion	663	CL loss through chip adhesion	663	33.2	12.3
	Total	**3,588**	**Total**	**3,588**	**179.4**	**66.4**

RME = rapeseed methyl ester; MIN = solvent raffinate

The quantities of base oil shown are used only for the production of the CL emulsion (last column, see Table 8). However, during the base oil production process, co-products are created which provide additional benefits during base oil production. Through allocation factors, as explained in section 4.1.1, the main and co-products are therefore weighted to determine the actual environmental impact of base oil production. The allocation factors applied (in %) for base oil production steps one to three with the corresponding quantities (in kg) are shown below (solvent raffinate: , Figure 12 rapeseed methyl ester: Figure 13). The database for the respective process chains for solvent raffinate[80] and rapeseed methyl ester[81] is taken from the literature.

[80] See Fehrenbach, H. (2005), pp. 27 – 30; Kolshorn, K.-U. and Fehrenbach, H. (2000), pp. A-47 et seqq.

[81] See Ecoinvent 3.2 (2015).

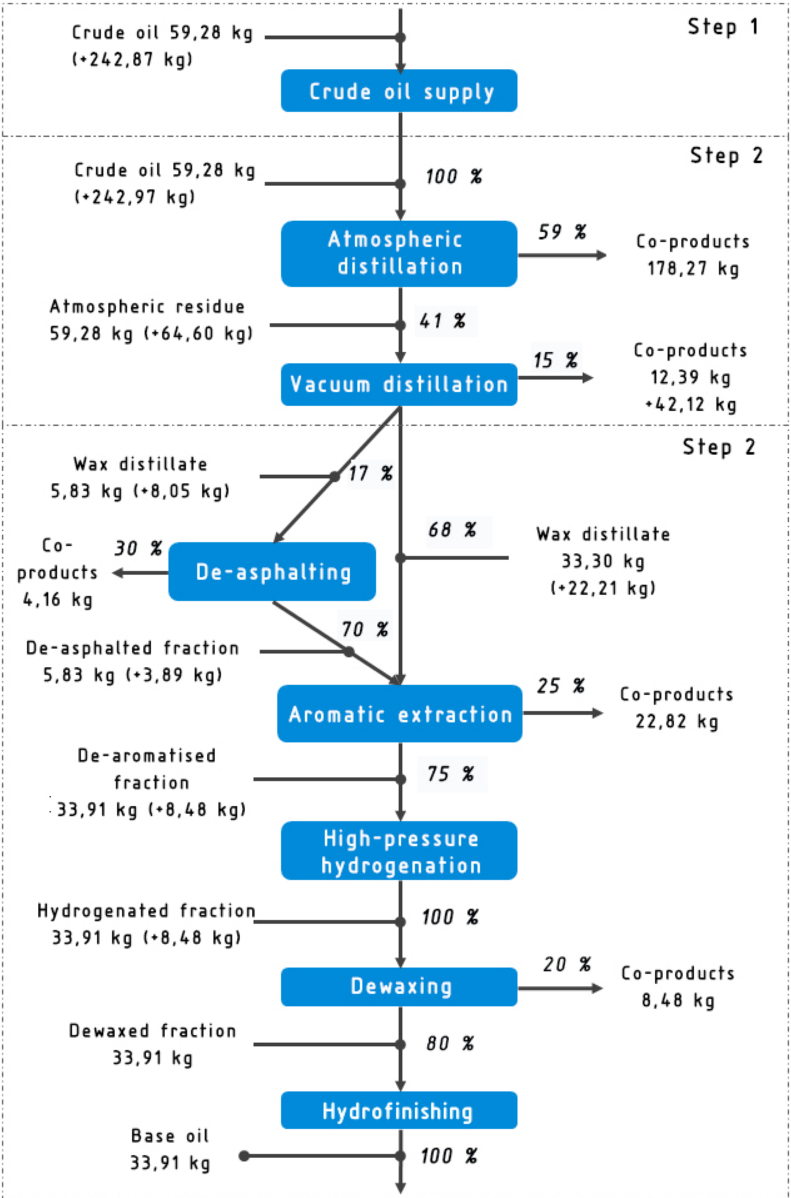


Figure 12: Process chain for production of the base oil solvent raffinate[82]

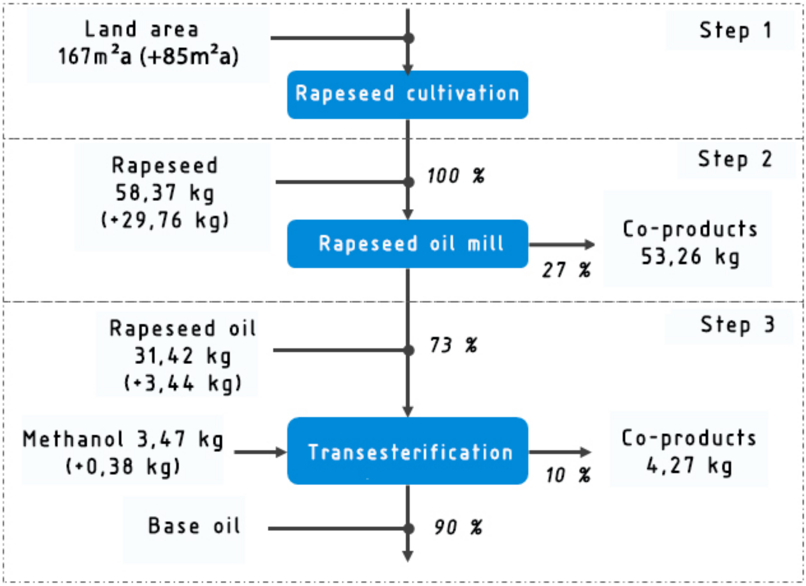


Figure 13: Process chain for production of the base oil rapeseed methyl ester

With the aid of the life-cycle assessment software Umberto NXT, the data and quantity structures determined were converted into a material flow model and the life cycle inventory required as the basis for the assessment was calculated. Data sets from Ecoinvent 3.2 were used for the background processes (provision of energy, etc.).

The comparative ecological assessment of the base oil alternatives focuses on the "input-side" costs, which are determined by the energy and resource demand. The resource water and the resource land use are considered separately. The ecological assessment is supplemented by looking at "output-side" emissions of greenhouse gases and their contribution to the global warming potential (GWP), which is expressed in CO_2 equivalents. In addition, the supply risk for the main raw materials crude oil and rapeseed is estimated by a criticality assessment.

[82] Quantities in kg, allocation factor based on mass in %, bold: quantities added to the base oil, normal font: quantities attributed to co-products

4.5 Economic assessment: Selection and quantification of cost items

4.5.1 Selection of cost items

The focus of the economic assessment is on the costs to the CL user, i.e. a small or medium-sized metalworking company. As a result, a detailed cost analysis of the manufacturing and disposal phase is obsolete. The interfaces between the manufacturing and utilisation phases and the utilisation and disposal phases are represented by the procurement prices (purchase prices) of the CL concentrate and the gate fees[83] of the responsible disposal company. These cost items already include the detailed production costs for the CL concentrate as well as the detailed costs for the disposal of the old emulsion. Since the economic assessment is carried out from the point of view of a CL user, the costs incurred in the production phase are only considered marginally, i.e. to compare market prices, and the costs incurred during the disposal phase are not included.

The following cost items are accounted for in the economic assessment during the utilisation phase:

- Procurement costs for the CL concentrate
- Water costs for mixing the CL concentrate with water
- Gate fees (disposal costs) for the old CL emulsion charged by the relevant disposal company

The costs incurred during the use phase of the CL circulation process, however, are not taken into consideration, since no differences arise here, based on the technological effect of the base oil alternatives, which has been determined to be the same.

[83] Gate fee = Disposal company's acceptance price for waste

4.5.2 Quantification of selected cost items

The costs are accounted for with realistic average values. For the cost estimates, primarily publicly available data was used and own estimates were made. In addition, selected manufacturers and formulators were contacted with the aim of assessing and verifying the assumptions made.

(1) Procurement costs for water-miscible CL concentrates

The procurement costs for water-miscible CL concentrates are made up of the costs for the base oil production, the profit margin of the base oil producer, the costs for the formulation (addition of additives) of the CL concentrate and the profit margin of the formulator.

From the perspective of the CL user, only the market or procurement price of the CL concentrates is relevant for the economic assessment, so that the production costs are not considered in detail. The procurement prices depend heavily on the quantities required, the suppliers of the CL user and the contracts and associated discounts. The market prices presented below can therefore only represent a snapshot independent of supplier relationships (volume discounts) and specific product prices.

The market prices for water-miscible CL concentrates are subject to fluctuations. In 2012, an expert survey[84] was carried out, which determined an average price of €3.64/kg for 2010 as the base year and an annual price increase of 2% for CL concentrates based on solvent raffinate. This results in an average price of €4.10/kg for the year 2016. In comparison with average prices on relevant internet exchanges, which set solvent-raffinate-based CL concentrate prices between €3.40/kg and €4.60/kg[85], the assumption of €4.10/kg can be verified as plausible.

The share of the base oil price in the market prices of the CL concentrate could only be obtained from one manufacturer, who receives his base oil at an average price of €0.95/kg.[86] This price was verified as plausible by the

[84] Internal expert survey on the price of water-miscible CL carried out by BiPRO in 2012

[85] The prices per CL concentrate are given as three to four euros per litre. At a density of 0.874 g/cm^3 (see safety data sheet BP Europa, SE at 15 °C: BP (2012), p. 5), kilogram prices are calculated from 3.40 euros to 4.70 euros.

[86] E-mail correspondence, 10.05.2016, Appendix B.

following consideration: with commercially available hydraulic oils, which are also used variously as multifunctional oils, the kilogram price is on average around €1/kg. The finished product consists of 95 - 99 % of a mineral oil cut as a base oil, which is comparable to that of the solvent raffinate.[87]

The market prices for rapeseed-methyl-ester-based CL concentrates also fluctuate strongly. A search of relevant internet exchanges revealed market prices of approx. €5/l to €10/l (€5.68/kg - €11.36/kg with a mean density of rape methyl ester of 0.88 g/cm^3).[88] It should be noted that rapeseed methyl ester is mainly used as biofuel. Wholesale prices for rapeseed methyl ester in the biodiesel market in 2015 were largely flat at € 0.7 per litre (excluding energy tax).[89] According to experts, it can be assumed that for niche markets such as CL production, the same base oil prices apply as the same certified properties must be provided.[90] This results in an average price of €0.80/kg for the rapeseed methyl ester base oil at a mean density of 0.88 g/cm^3. This base oil price is slightly lower than that of solvent raffinate at around €0.95 - 1/kg. Since it was determined for this study that the CL concentrate production should be identical for both base oil alternatives, but the literature describes rape methyl ester-based CL concentrates as more expensive[91], the purchase price for the CL concentrate based on rapeseed methyl ester is determined to be €5.68/kg according to the lower researched price range.

(2) Cost of water supply to mix the CL emulsion

Based on the assumption that the amount of water to be mixed with the CL concentrate is the same, the same costs result for both base oil variants.

Water consumption is set at the industrial water price. The weighted average for 2012 was €1.735/m^3. [92]For the year 2016, a value of around €1.80/t is assumed as average industrial water price.

87 Telephone information, 17.05.2016, Appendix B.
88 See information from available safety data sheets, for example from SysKem (2011), p. 4.
89 See Burghardt, B. (2015).
90 Telephone information, 19.05.2016, Appendix B.
91 See Möller, U.J. and Nassar, J. (2013), p. 91.
92 See ZfK (2012).

(3) Disposal costs (gate fees of the responsible disposal company)

Disposal consists of splitting the old emulsion into an aqueous phase and a waste oil phase, waste water treatment, waste oil combustion and the energy costs required. Since the CL quantities to be disposed of are transferred directly to the disposal company, splitting of the costs into waste water treatment and waste oil combustion is not required. For the economic analysis, the gate fees to be paid to the disposal company are calculated. These are set at the same level for both CL alternatives, since the same disposal method is defined according to Figure 11.

The disposal costs per cubic metre of spent emulsion vary by region in Germany and fluctuate due to the economic situation. A survey of German disposal companies determined a range of €120 - 180/m^3 for gate fees. Among other things, this is due to limited waste treatment capacity, which is reflected in rising prices, especially in times of economic growth.

For the present study, the average of the range of disposal costs – €150/m^3 – is taken for both CL alternatives. This corresponds to a cost of €150/t, as the CL emulsion consists of 95 % water and a density of 1 g/cm^3 is assumed for simplicity's sake.

In summary, from the point of view of the CL user the following specific costs (Table 9) result for procurement, mixing of the CL emulsion and disposal of the old emulsion.

Table 9: Costs for procurement of CL concentrate, water consumption and disposal

Cost item	Solvent raffinate	Rapeseed methyl ester
Market price CL concentrate (€/kg)	€4.10/kg	5.68 €/kg
Cost of water consumption (€/t)	1.80 €/t (0.0018 €/kg)	1.80 €/t (0.0018 €/kg)
Disposal costs (€/t)	150 €/t (0.150 €/kg)	150 €/t (0.150 €/kg)

For the economic assessment, the reference to the functional unit is also established by linking the specific costs presented to the data from the quantity structure of Table 8.

5 RESULTS OF THE ENVIRONMENTAL AND ECONOMIC ASSESSMENT

5.1 Results of the ecological assessment

5.1.1 Cumulative energy demand

Cumulative energy demand (CED) is "... the entire demand, valued as primary energy, which arises in connection with the production, use and disposal of an economic good (product or service) or which may be attributed respectively to it in a casual relation"[93]. In addition to the energetic use, the non-energetic consumption and substance-related energy content are taken into account.[94] The information is given in megajoule equivalents (MJ-eq).

Non-energetic consumption includes the use of oil for the production of the base oil solvent raffinate (MIN). This quantity of material used is assigned to the CED via the gross calorific value (45.8 MJ/kg).[95] The harvested amount of rapeseed contains a substance-bound energy content (24.07 MJ/kg of energy in biomass)[96] and is taken into account in the calculation of the CED for the base oil variant rapeseed methyl ester (RME).

The CED is grouped by primary energy sources and summarised here in the superordinate groups "CED, exhaustible" and "CED, renewable". The following allocation was made:

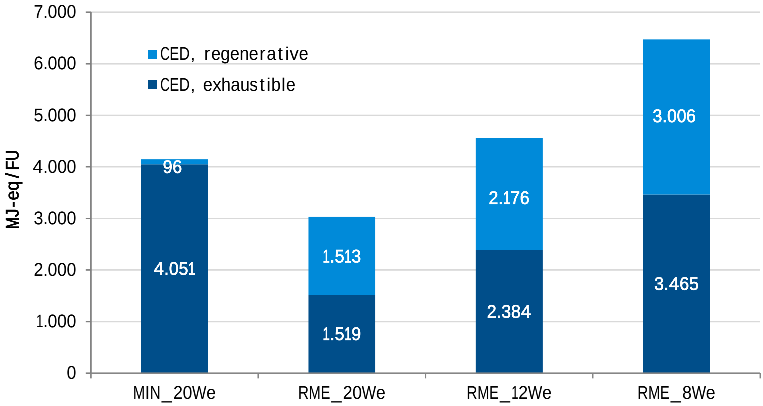
CED, exhaustible:	CED-fossil, nuclear, biomass/primary forest
CED, renewable:	CED biomass, wind, solar, water power

For the calculation of the CED values, the method provided in Ecoinvent 3.2 is used. The primary energy assessment is based on the gross calorific values (upper heating values).

The CED values shown below are based on the results of the life cycle inventory analysis and are each related to the functional unit (FU). Figure 14 shows the proportions of "CED, exhaustible" and "CED, renewable" of the

[93] VDI 4600:2012-01, p. 6.
[94] Kosmol, J. et al. (2012), p. 11.
[95] See Ecoinvent 3.2 (2015).
[96] See Ecoinvent 3.2 (2015).

base oil variants solvent raffinate (MIN_20Wo) and rapeseed methyl ester (RME_20Wo) for an emulsion life of 20 weeks. In addition, the results for the base oil rapeseed methyl ester with shortened service life of twelve weeks (RME_12Wo) and eight weeks (RME_8Wo) are shown for the entire life cycle.



RME: rapeseed methyl ester, MN: solvent raffiante

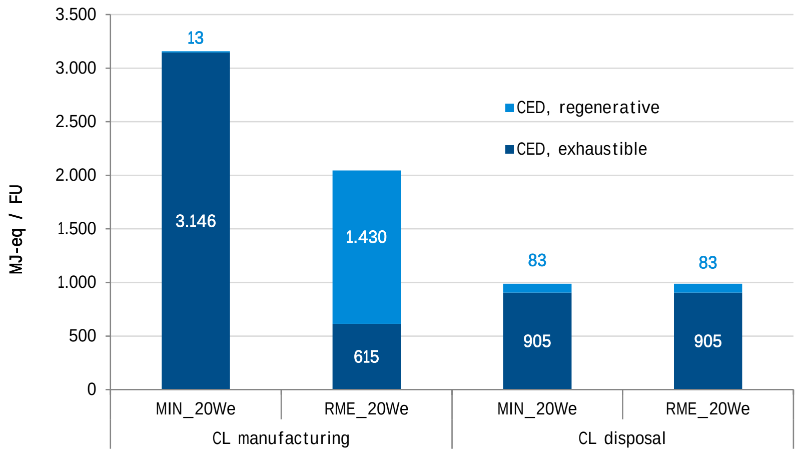
Figure 14: Cumulative energy demand (CED) per functional unit (FU) for the entire life cycle

It can be seen that the base oil variant rapeseed methyl ester (RME_20Wo) causes the lowest CED for an emulsion life of 20 weeks. The significant substance-related contribution of the rapeseed to "CED, renewable" of 1,513 MJ-eq/FU is evident here (energy in the biomass = 1,405 MJ-eq/FU).

The non-energetic consumption of crude oil in the base oil variant solvent raffinate (MIN_20Wo) contributes a total of 4,051 MJ-eq/FU to "CED, exhaustible" with 2,715 MJ-eq/FU.

If a shortened service life of twelve weeks is considered, the CED of the base oil variant rapeseed methyl ester (RME_12Wo) already exceeds the CED for the mineral-oil-based solvent raffinate (MIN_20Wo). 57 % of the increase is due to the rise in "CED, exhaustible", which is the result of both the production and, in particular, the disposal of the emulsion, and 43 % of the increase is due to the rise in in "CED, renewable" arising from the component of the substance-related energy contribution of rapeseed.

For a detailed assessment of the CED, the base oil variants solvent raffinate (MIN_20Wo) and rapeseed methyl ester (RME_20Wo) have been subdivided into the life phases CL manufacturing and CL disposal with a service life of 20 weeks in Figure 15. There is no consumption to record for the utilisation phase, since, in accordance with the assumptions, the energy demand for the operation of the machines etc. for both CL emulsions considered is the same and their environmental contribution is cancelled out in the comparative ecological assessment.



RME: rapeseed methyl ester, MN: solvent raffinate

Figure 15: Cumulative energy demand (CED) per functional unit (FU), subdivided into life cycle phases

This illustration makes it clear that the CED is the same for the disposal phase of both base oil variants. The same energy consumption is required for emulsion splitting, waste water treatment and waste oil combustion for all alternatives, in accordance with the assumptions. Emulsion splitting accounts for the largest share of the CED for the disposal phase, with 890 MJ-eq/FU for "CED, exhaustible" and 82 MJ-eq/FU for "CED, renewable".

The differences in total CED values are therefore due to the manufacturing phase. These CED values are dominated by the non-energetic contribution of oil to "CED, exhaustible" and the material-related energy contribution of the rapeseed to "CED, renewable". For solvent raffinate, the material-related proportion of the total CED for the manufacturing phase is 86% (2,715 MJ-eq/FU of 3,159 MJ-eq/FU) and 69% for rapeseed methyl ester (1,405 MJ-eq/FU of 2,044 MJ-eq/FU). If only energetic use is considered, the solvent raffinate makes the smallest contribution to the CED.

5.1.2 Cumulative raw material demand

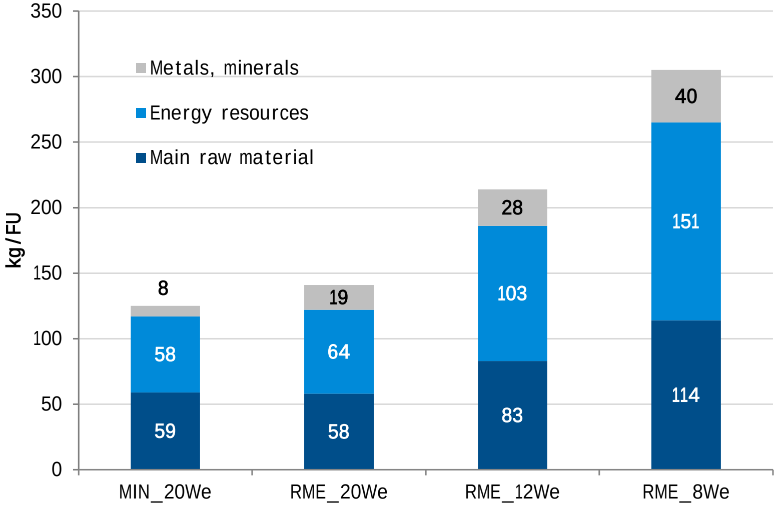
The assessment indicator cumulative raw material demand (CRMD) is the sum of the quantities of raw materials used along the value chain to provide a product. The CRMD covers all raw materials used to manufacture and transport a product, including energy resources. Uneconomic substances and mixtures, such as unused abstraction, are not taken into account.[97] The CRMD is also defined as the sum of all raw materials entering a system – except water and air – expressed in units of weight [98]. If the entire life cycle (cradle-to-grave) of a product is considered, the raw material consumption can be differentiated according to life phases. Raw materials to be considered are energy raw materials as well as mineral, fossil and biotic raw materials, which are still to be differentiated into primary and secondary raw materials.[99] In the life cycle inventory analysis, all primary raw materials that enter the product life cycle were quantified, grouped by raw materials and energy raw materials and aggregated. Secondary raw materials were not used in the product systems considered here.

The fossil primary raw material crude oil is used both materially (production of the base oil solvent raffinate) and energetically (energy supply and transport processes). Therefore, crude oil as a raw material for material use and the biotic raw material rapeseed, which is produced by cultivation and the actual function of which is as a raw material for the production of the base oil rapeseed methyl ester, are considered separately under the term "main raw material".

The group "energy raw materials" contains the quantity of oil used for energy purposes and other energy raw materials recorded as a mass, such as natural

[97] Kosmol, J. et al. (2012), p. 12.
[98] Giegerich, J. et al. (2012), p. 22.
[99] See VDI 4800 Part 2, p. 7.

gas (volume conversion into mass using the density 0.78 kg/m ^{3})[100], coal, peat and uranium. The group "Metals, minerals" includes all mineral primary raw materials used for the provision of energy, operating materials, infrastructure, etc. Figure 16 shows the CRMD over the entire life cycle in terms of the functional unit.



RME: rapeseed methyl ester, MN: solvent raffinate

Figure 16: Cumulative raw material consumption (CRMD) per functional unit (FU) for the entire life cycle

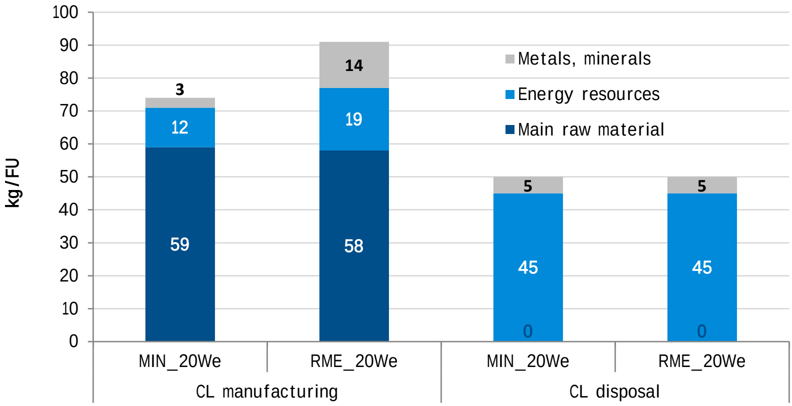
The base oil variant rapeseed methyl ester requires higher raw material consumption than the variant solvent raffinate of 17 kg/FU (RME_20Wo: 142 kg/FU, MIN_20Wo: 125 kg/FU). The mineral raw materials play a minor role. The main contribution to the CRMD over the entire life cycle comes from the main raw materials (MIN_20Wo: 59.3 kg/FU, RME_20Wo: 58.4 kg/FU) and the energy raw materials (MIN_20Wo: 58 kg/FU, RME_20Wo: 64 kg/FU).

If the service life of the CL emulsion based on rapeseed methyl ester is shortened to twelve or eight weeks, the CRMD values increase significantly and

[100] See Klöpffer, W. and Grahl, B. (2009), p. 84.

show a higher resource requirement by a factor of 1.7 (RME_12Wo) or a factor of 2.6 (RME_8Wo) over the entire life cycle compared to the base oil variant solvent raffinate (MIN_20Wo).

A subdivision in the life cycle phases shows that the greatest proportion of energy resources is required in the disposal phase (Figure 17).



RME: rapeseed methyl ester, MN: solvent raffinate

Figure 17: Cumulative raw material consumption (CRMD) per functional unit (FU), subdivided according to life cycle phases

As with the CED, the CRMD is the same in the disposal phase for the service life of 20 weeks for the CL variants, with the main contribution (99% of energy resources) resulting from the energy supply for emulsion splitting.

5.1.3 Water consumption

By definition, the water commodity group is not included in the CRMD indicator and is considered separately. Only fresh water, which is taken from nature and is consumed by evaporation, irrigation in agriculture, product integration, etc., is evaluated, i.e. "that part of water use that is no longer available to the hydrological catchment area"[101]. The use of cooling and sea water is not taken into account.

[101] VDI 4800 Part 2, p. 10.

As part of the life cycle inventory analysis, the corresponding amounts of fresh water resources (river, sea, groundwater, etc.) were quantified and aggregated. This also corresponds to the procedure of the environmental assessment method ReCiPe 2008[102] for determining the indicator water consumption, which is expressed in cubic meters (Figure 18).

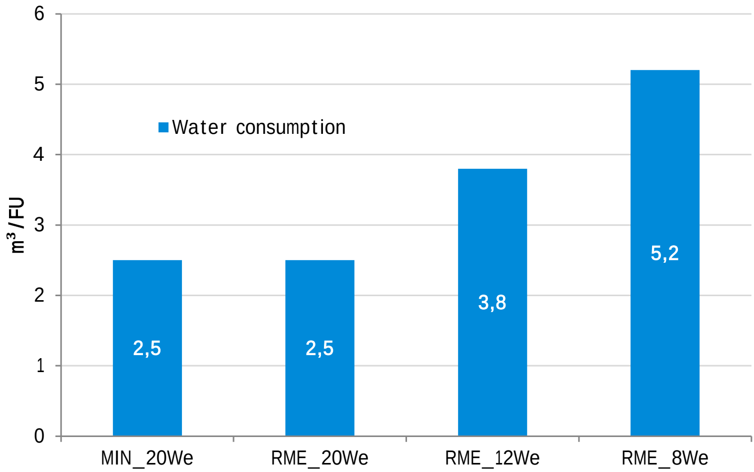
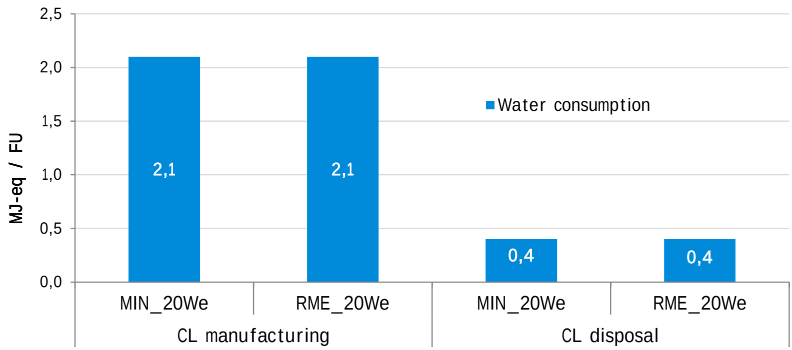


Figure 18: Water consumption per functional unit (FU) for the entire life cycle of CL variants

By comparison, the base oil variants with a service life of 20 weeks have the same water consumption of 2.5 m^3 per functional unit, 82 % of which is based on the required amounts of drinking water and the treatment work. A shortened service life of the rapeseed methyl ester of twelve or eight weeks increases the water consumption by a factor of 1.5 (RME_12Wo) or 2.1 (RME_8Wo).

Differentiation into the various life cycle phases again shows that the major proportion of water consumption for both base oil variants comes from the CL-production phase (Figure 19).

[102] See Goedkoop, M. et al. (2013).



Water RME: rapeseed methyl ester, MN: solvent raffinate

Figure 19: Water consumption per functional unit (FU), subdivided into life cycle phases

The water consumption required in the production phase includes the provision of drinking water for mixing with the concentrate to obtain the 5 % CL emulsion. The required amount of drinking water and the treatment work are the same for both variants with a service life of 20 weeks and result in 2.1 m^3/FU. Thus, more than 90 % of the water consumption in the production phase of the base oil variants solvent raffinate and rapeseed methyl ester is determined by the supply of drinking water (Figure 19).

5.1.4 Land use

Land use is also included in natural resources. It is subdivided according to use, e.g. arable, pasture, forest, building, traffic or landfill areas. Land use considers the use of a certain area during a certain period of use. The unit of measurement is thus square metres per year (m^2*a).

For the assessment of land use, the same types of land are considered here as are used in the environmental assessment method CML 2001[103]. They are divided into the two groups “agricultural areas” and “residential areas” for a better overview. The following land uses are assigned to them:

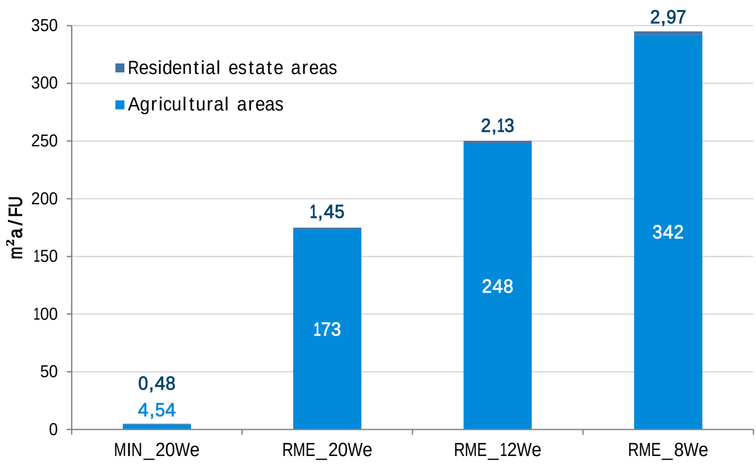
Agricultural areas: Arable land for annual and perennial crops, pasture, shrub and forest areas

[103] See Giunée, J. B. (ed.) (2002).

Residential areas: Industrial, urban, construction site, traffic, mining and landfill sites

Based on the life cycle inventory data, the respective land uses were quantified and aggregated. In relation to the functional unit, the values shown in Figure 20 result for land use for the base oil alternatives.

The base oil variant rapeseed methyl ester has the largest use of land over its entire life cycle for all service lives. This can be attributed to the agricultural area required for rapeseed cultivation. Based on a yield per hectare of 3500 kg of rapeseed/(ha*a)[104], the land use required for the 20-week service life is 167m^2*a/FU for the provision of 58.4 kg rapeseed/FU. With reduced lifetimes of twelve and eight weeks respectively, land use increases by a factor of 1.4 and 2 for the provision of the rapeseed for the functional unit (Figure 20).



RME: rapeseed methyl ester, MN: solvent raffinate

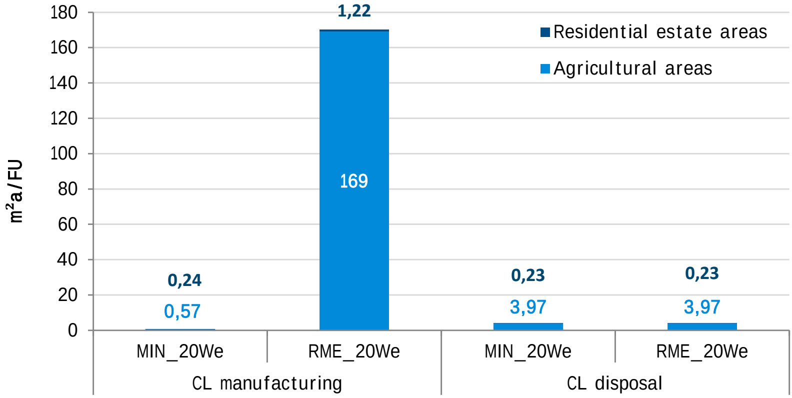
Figure 20: Land use per functional unit (FU) for the whole life cycle

Compared to the base oil variant solvent raffinate (MIN_20Wo), the base oil variant rapeseed methyl ester (RME_20Wo) requires 38 times more land, with a shortened service life of twelve weeks (RME_12Wo) almost 55 times

104 See Ecoinvent 3.2 (2015).

more land and for a shortened service life of eight weeks (RME_8Wo) about 75 times more land. The residential space required is negligible for all variants considered.

Differentiation into the life cycle phases of manufacturing and disposal clarifies the facts (Figure 21).



RME: rapeseed methyl ester, MN: solvent raffinate

Figure 21: Land use per functional unit (FU), subdivided into life cycle phases

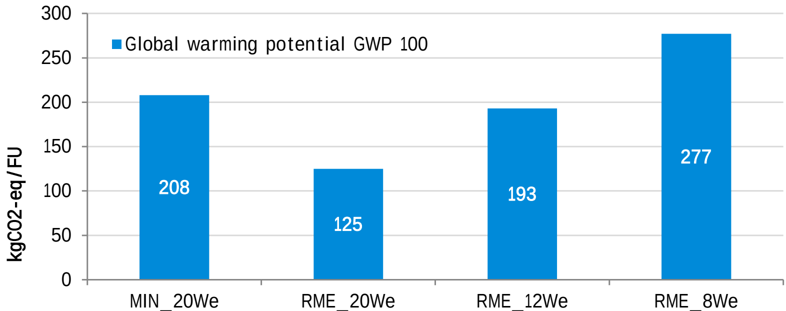
In the production phase of the base oil rapeseed methyl ester (service life of 20 weeks), the largest proportion of land – 169 m^2*a/FU – is used. Land use for the disposal phase is the same for the CL variants with a service life of 20 weeks and is dominated by the contribution of the energy supply for emulsion splitting.

5.1.5 CO_2 equivalents

Emissions of greenhouse gases cause them to enter the atmosphere, stay there and absorb and reflect heat radiation (infrared radiation), which heats the earth's surface. This natural process is amplified by increasing anthropogenic emissions of greenhouse gases, causing global warming and contributing to climate change. The greenhouse gases include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (laughing gas, N_2O). They have different absorption capacities and persist for different times. The potential with which they contribute to the greenhouse effect is expressed in relation to the lead substance CO_2 (CO_2 equivalents). The global warming potential

(GWP) is used as an indicator. Due to the different durations that greenhouse gases remain in the atmosphere, the time frame under consideration must be specified. A reference period of 100 years (GWP100) is standard. The data is given in kg CO_2 equivalents (kg CO_2-eq). This indicator is widely used in science and is often employed for environmental assessments.

The equivalence factors according to IPCC 2007[105] were used to assess the emissions of greenhouse gases determined in the life cycle inventory analysis. In Figure 22, the global warming potential GWP100 of the base oil variants for the entire life cycle is shown. Based on the functional unit and with an emulsion life of 20 weeks, the base oil variant rapeseed methyl ester has the lowest global warming potential (RME_20Wo: 125 kg CO_2-eq/FU) compared to the base oil variant solvent raffinate (MIN_20Wo: 208 kg CO_2-eq/FU).



RME: rapeseed methyl ester, MN: solvent raffinate

Figure 22: Greenhouse gas potential GWP100 per functional unit (FU) for the whole life cycle

If the service life of the CL emulsion based on rapeseed methyl ester is shortened to twelve or eight weeks, the GWP100 increases significantly. With a service life reduction to twelve weeks, the global warming potential of 193 kg CO_2-eq/FU lies in the range of the solvent raffinate variant (208 kg CO_2-

[105] See IPCC (2007).

eq/FU). If the service life is reduced to eight weeks, the GWP100 exceeds this value by 69 kg CO_2-eq/FU.

A more detailed analysis along the lifecycle phases for all variants shows that the global warming potential of the rapeseed methyl ester variants with a service life of 20, twelve and eight weeks increases more during the disposal phase than during the production phase (Figure 23). The main driver in the disposal phase is the energy supply process for emulsion splitting, which is mainly linked with CO_2 emissions.

By contrast, the main polluter in the production phase is agricultural rape cultivation and fertilizer, which releases CO_2 and N_2O emissions. A detailed analysis shows that the process of agricultural rapeseed cultivation is the largest producer of greenhouse gases and contributes 48 kg CO_2-eq/FU (RME_20Wo) to the GWP100. This is also due to the lower GWP100 of the base oil variant solvent raffinate (MIN_20Wo) of 41 kg CO_2-eq/FU compared to a GWP100 of 59 kg CO_2-eq/FU of the rapeseed methyl ester variant (RME_20Wo) in the production phase. In the case of the base oil variant solvent raffinate, in addition to the crude oil supply (14.5 kg CO_2-eq/FU), the energy supply in the third base oil production step (20 kg CO_2-eq/FU) is mainly responsible for the GWP100 and is predominantly due to the CO_2 emissions.

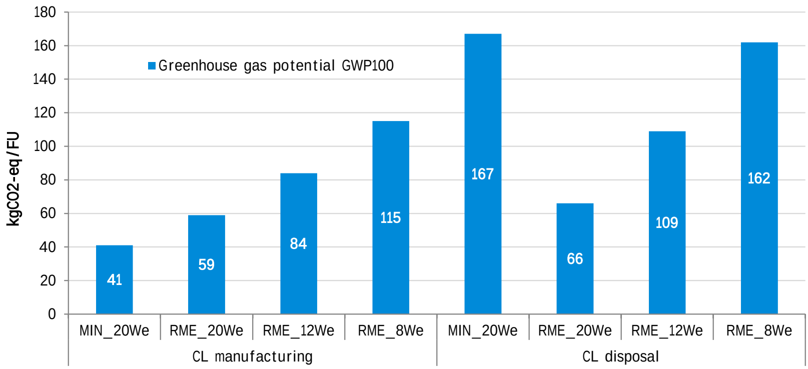


Figure 23: Global warming potential GWP100 per functional unit (FU), subdivided into life cycle phases

In the CL disposal phase, the global warming potential for the mineral-oil-based variant solvent raffinate (MIN_20Wo) is 167 kg CO_2-eq/FU, which is about 100 kg CO_2-eq/FU higher than that of the rapeseed oil-based variant (RME_20Wo). A contribution to the GWP100 in the disposal phase comes from the energy supply for emulsion splitting (59.5 kg CO_2-eq/FU) and is the same for the variants rapeseed methyl ester and solvent raffinate with a service life of 20 weeks. The contribution to the GWP100 caused by the treatment of the aqueous phase is identical for these variants (MIN_20Wo, RME_20Wo),too , albeit comparatively low (0.35 kg CO_2-eq/FU).

Differences result from the emissions during waste oil combustion (MIN_20Wo: 68.6 kg CO_2-eq/FU, RME_20Wo: 4.3 kg CO_2-eq/FU) and combustion of the CL chip adhesion (MIN_20Wo: 38.9 kg CO_2-eq/FU, RME_20Wo: 1.8 kg CO_2-eq/FU). This is due to the CO_2 adjustment for the rapeseed-oil-based CL emulsion, which takes into account their biogenic carbon content. This does not contribute to the greenhouse effect, since it was previously absorbed in plant growth from the atmosphere.

Thus, the "output-side" indicator GWP100 gives rise to an advantage for the base oil variant rapeseed methyl ester (RME_20Wo), because the biogenic carbon is released without altering the CO_2 balance. However, this effect diminishes as the service life falls, since the increasing emissions from the production and disposal phases exceed the total global warming potential of the mineral oil-based solvent raffinate variant after about twelve weeks.

5.2 Raw material criticality

To evaluate raw material criticality, a criticality analysis is carried out in accordance with VDI 4800 Part 2."The objective of the criticality analysis is to identify raw materials of a raw material-using system (reference system) that serve essential functions for this system while their supply is associated with risks. The criticality analysis allows an assessment of the vulnerability of a reference system (e.g. a company) to disruptions in the supply of specific raw materials."[106]

Crude oil and oilseed rape (rapeseed or rapeseed oil) were identified as the main raw materials essential for the production of the base oils considered here. For these raw materials the criticality dimension of supply risk was determined on the basis of the criteria and indicators specified in the VDI guideline[107]. Similar results were already available for the fossil organic raw material crude oil[108], which were adopted here. For the biotic raw material oilseed rape (rapeseed/rapeseed oil) a separate assessment was carried out, which is justified as follows:

(1) Geological, technical and structural criteria

(a) Static range

An indicator of the static range is the "ratio of reserves to global annual production". However, as biotic raw materials represent renewable raw materials, the term reserve must be redefined and differentiated between the cultivation and harvesting of biotic raw materials. For biotic raw materials (such as oilseed rape) provided by cultivation, the default value 0.7 is set as the indicator value.

(b) Co-product/By-product

If a raw material is obtained as a by-product or co-product, its availability depends on the supply of or demand for the main product. The classification is therefore based on the indicator "Degree Co-product/By-product". Since

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106 VDI 4800 Part 2: Draft, p. 11.

107 See VDI 4800 Part 2: Draft, p. 13.

108 See VDI 4800 Part 2:Draft, Appendix B, Tab. 4.

rapeseed oil can be identified as the main product over rapeseed meal, the indicator value 0 (raw material is entirely recovered as main product) is determined.

(c) Recycling

On the one hand, recycling in the sense of material recycling of end-of-life waste protects natural resources and, on the other hand, offers secondary raw materials as a substitute or supplement for primary raw materials. An indicator of this criterion is the "spread of functional end-of-life recycling technologies". The end-of-life waste of CL based on rapeseed methyl ester is the old emulsion which is sent for thermal recycling after emulsion splitting. Recycling of the materials does not exist. Therefore, the indicator value is set to 1 (recycling not established).

(d) Logistical constraints

Transport distances, trade links and storability are the parameters that determine the indicator “economic viability of storage and transport". Since the assumption was made in this study that the raw material rapeseed is cultivated in Germany, the indicator value 0 is applied (storage and/or transport unproblematic and economically viable).

(e) Constraints due to natural disasters

The availability of biotic raw materials may be affected by natural events (e.g. drought, pest infestation). As there is still no adequate database for quantifying the susceptibility of raw material extraction to natural events, standard indicator values are defined depending on the growing area. For oilseed rape, which is generally cultivated worldwide, the indicator value is therefore 0.3 (biotic raw materials whose occurrence/main growing region is distributed over several continents).

(2) Geopolitical and regulatory criteria

(a) Country concentration of reserves

With the increasing spread of reserves across multiple countries, the risk of exploiting market power is reduced. The Herfindahl-Hirschmann Index (HHI), which is defined as the sum of the squared share values of the reserves of all market participants, is used as an indicator for the country risk of the reserves. For biotic raw materials that are obtained through cultivation, the HHI refers to the worldwide cultivated areas. The calculation of the HHI for oilseed rape is based on the statistical values of FAOSTAT[109] for the reference year 2013. For this purpose, the 19 countries with the largest shares were used, with the result that a total of 95% of the world acreage was taken into account. The calculated HHI is 0.149. This results in an indicator value of 0.3 (HHI <0.15 low reserve concentration).

(b) Country concentration of production

Concentrating raw material production in a few countries increases the risk of market power being exercised and can have a negative impact on raw material availability. The Herfindahl-Hirschmann Index (HHI) is also used here as an indicator and the sum of the squared share values of the production volumes of all market participants is calculated. The calculation of the HHI for oilseed rape was carried out for the reference year 2013 with the statistical data for worldwide production quantities provided by FAOSTAT[110]. For this, 19 countries were considered in the order of their production volumes. They cover a total of 95% of world production. The calculated HHI is 0.144, giving an indicator value of 0.3 (HHI <0.15 low concentration of production).

(c) Geopolitical risks of global production

"A key factor determining the access to raw materials is the political stability of the exporting countries and the extraction regions."[111] In particular, countries with persistent political unrest and violent conflicts can affect the availability of raw materials. The determination of the Political country risk indicator (PCI) therefore takes into account characteristics such as the right to co-determination and the probability of destabilisation quantified by the two World Bank indicators “voice and accountability” and “political stability and absence of violence”. The PCI for the biotic raw material oilseed rape was calculated according to the formulas given in the VDI Guideline[112], based on the percentile values for "voice and accountability" and "political stability

[109] See FAOSTAT (2013), Area harvested and Rapeseed, 2013, World List.

[110] See FAOSTAT (2013), Production Quantity and Rapeseed, 2013, World List.

[111] VDI 4800 Part 2: Draft, p. 18.

[112] See VDI 4800 Part 2: Draft, pp. 18 - 19.

and absence of violence" for the reference year 2013 listed by the World Bank[113] in relation to the nine largest producing countries in the world (Canada, China, India, Germany, France, Australia, Poland, Ukraine, UK), which account for 85 % of world production. The calculated PCI value is 0.39, from which the indicator value 0.3 (0.15 <= PCI <0.5, moderate relative political country risk) is derived.

(d) Regulatory situation for raw material projects

Regulatory framework conditions that result, for example, from economic, tax and environmental policies can also influence the availability of raw materials. The calculation of the “regulatory country risk indicator” (RCI) takes into account the four World Bank indicators “rule of law”, “regulatory quality”, “control of corruption”, and “government effectiveness”. The RCI for the biotic raw material rapeseed was calculated according to the formulas given in the VDI Guideline[114], on the basis of the World Bank[115] percentile values for the specified World Bank indicators. Here, too, the figures refer to 2013 for the world's nine largest manufacturing countries, covering 85 % of global production. The determined RCI value is 0.27. This results in the indicator value 0.3 (0.15 <= RCI <0.5, moderate relative regulatory country risk).

(3) Economic criteria

(a) Company concentration of global production

Since raw material producers can also exert a considerable influence on the supply of raw materials and hence raw material prices, a high concentration of companies indicates a supply risk. The indicator used is the "Herfindahl-Hirschmann-Index (HHI) of companies". However, no values for calculating the HHI could be determined for the biotic raw material rapeseed (rapeseed/rape oil). Since both rapeseed cultivation and the other stages of processing (rapeseed oil production and transesterification) are established procedures worldwide and no company has a monopoly position, an indicator value of 0.3 (low company concentration) was estimated qualitatively.

[113] See Kaufmann, D., Kraay, A. and Mastruzzi, M. (2010).
[114] VDI 4800 Part 2:Draft, pp. 19 - 20.
[115] See Kaufmann, D; Kraay, A. and Mastruzzi, M. (2010).

(b) Global demand impetus

An increasing demand for raw materials requires an expansion of the supply of raw materials and is often associated with price increases. The "level of demand growth" is used as the indicator of supply risk. The risk grows the more demand increases and the more erratic it is. The biotic raw material rapeseed, in addition to its importance as a food, has already gained increasing demand as a raw material for biodiesel production. Demand and supply have been relatively parallel in recent years. For example, the demand for biodiesel in Germany has remained roughly constant since 2011, with the import of oilseed rape increasing and domestic rapeseed acreage declining.[116] A future trend for global demand for oilseeds will be towards a further increase, with the main drivers being the growing population and the use of vegetable oils for energy. At the same time, it is predicted that the acreage for major oilseeds will expand and prices for vegetable oils will continue to rise.[117] For the indicator "level of demand growth", therefore, a value of 0.3 (demand grows in parallel with global economic growth) is estimated.

(c) Substitutability

The ability to replace a commodity with an alternative commodity has an impact on supply risk. Functional and economic aspects play a key role here. Alternatives with a vegetable, animal or mineral basis could be identified as a substitute for rapeseed oil or rapeseed methyl ester for use as a base oil for wmb CL. The indicator "Technical and economic feasibility of of substitutions in main applications" is therefore estimated at 0.3 (substitutability at low cost).

(d) Raw material price fluctuations

Formally, raw material price fluctuations can be expressed using the volatility, which can ideally be calculated as a current calculation based on one year's data.

116 See Fachagentur Nachwachsende Rohstoffe (FNR) (2013), p. 29.

117 See Fachagentur Nachwachsende Rohstoffe (FNR) (2014b), p. 49.

The internet platforms "index mundi"[118] and "Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk eV" (CARMEN eV)[119] were identified as sources for current price developments that capture prices for rapeseed oil and were used for the assessment. These sources allow a qualitative assessment of price changes, in the case of index mundi at monthly intervals over the past six months and in the case of C.A.R.M.E.N. eV at two-monthly intervals from November 2012 to November 2015. These price developments for rapeseed oil are based on expected price fluctuations of a moderate extent and do not lead to high supply uncertainty in this commodity market.

Since no binding assessment was made, for example by DERA, the indicator “annualised price volatility” was estimated qualitatively according to the observable intervals of price developments for rapeseed oil at 0.3 (price volatility >= 5 %, <10 %).

Figure 24 shows the indicator values for the biotic raw material rapeseed (rapeseed oil) and the indicator values for the fossil organic raw material crude oil taken from the VDI Guideline.

118 See index mundi (2016).
119 See C.A.R.M.E.N. e.V. (2016).

Raw material/element	Geological, technical and structural indicators					Geopolitical and regulatory indicators				Economic indicators			
	Ratio of reserves to annual global production	Degree of combined/secondary production	Degree of dissemination of functional EoL recycling technologies	Cost-effectiveness of storage and transportation	Degree of distribution of natural resources/cultivation areas	Herfindahl-Hirschman index of reserves	Herfindahl-Hirschmann index of country production	Political country risk	Regulatory country risk	Herfindahl-Hirschmann index of companies	Degree of increase in demand	Technical feasibility and cost-effectiveness of substitutions in main applications	Annualised price volatility
Biotic raw materials													
Rapeseed/rape oil	0,7	0	1	0	0,3	0,3	0,3	0,3	0,3	*0,3*	*0,3*	*0,3*	*0,3*
Fossil organic raw material													
Crude oil	0,3	0	0,3	0,3	0	0,3	0,3	0,7	0,3	0,3	0,7	0	1

Legend: cell filling white: data calculated and sources known and reported; grey striped: default value prescribed by guideline; grey: expert assessment

Figure 24: **Assessment of supply risk for oilseed rape and crude oil**

5.3 Results of the economic assessment

5.3.1 Procurement and water costs

From the point of view of the CL user, the costs necessary for the procurement of the CL concentrate amount to €375.97/a with a service life of 20 weeks for the mineral-oil-based variant solvent raffinate (MIN_20Wo). The annual water costs for manufacture of the emulsion amount to €3.13/a. In sum, the base oil variant solvent raffinate (MIN_20Wo) incurs an annual cost of €379.10 (Table 10).

Table 10: Procurement and water costs for the functional unit in euros/a

Variant	CL concentrate	Procurement costs CL concentrate	Amount of water	Water costs	Total cost
	kg/a	€/a	kg/a	€/a	€/a
MIN_20Wo	91.7	€375.97	1,741	€3.13	€379.10
RME_20Wo	91.7	€520.86	1,741	€3.13	€523.99
RME_12Wo	130.7	€742.38	2,482	€4.47	€746.84
RME_8Wo	179.4	€1,018.99	3,409	€6.14	€1,025.13

Based on the fixed procurement price of €5.68/kg for the rapeseed-methyl ester-based CL concentrate, the total costs including the water costs for the base oil variant rapeseed methyl ester (RME_20Wo) are approximately 1.4 times higher than for the solvent raffinate version (MIN_20Wo). If the service life is shortened to twelve or eight weeks, the costs increase twice over or 2.7 times.

5.3.2 Disposal costs

The disposal costs for the old emulsion relate to the output, without taking into account the quantities that are removed via the chip adhesions from the cooling lubricant system under consideration. The energy required for emulsion splitting, which increases from 93.6 kWh/FU to 156 kWh/FU or 234 kWh/FU for a shorter service life, is included in the disposal costs, as they are to be understood as part of the gate fees. The disposal costs for the base oil variants solvent raffinate (MIN_20Wo) and rapeseed methyl ester (RME_20Wo) thus amount to €175.50/a with a service life of 20 weeks at a specific price of €150/t (Table 11).

Table 11: Cost of the functional unit for disposal in euros/a

Variant	Waste emulsion	Disposal costs
	kg/a	€/a
MIN_20Wo	1,170	€175.50
RME_20Wo	1,170	€175.50
RME_12Wo	1,950	€292.50
RME_8Wo	2,925	€438.75

A shorter service life of twelve or eight weeks leads to increased disposal costs of €292.50 or €438.75 per year. This corresponds to a cost increase by a factor of 1.7 or 2.5 compared to the variants MIN and RME with a service life of 20 weeks.

5.3.3 Total costs from the point of view of the CL user

Figure 25 shows the total costs for all considered CL variants, subdivided according to cost items. Two additional scenarios are also presented, which calculate lower hypothetical procurement prices for rapeseed-methyl-ester-based CL concentrates (RME_12Wo_I, RME_8Wo_I) so that the total costs correspond to those of the mineral-oil-based variant (MIN_20Wo).

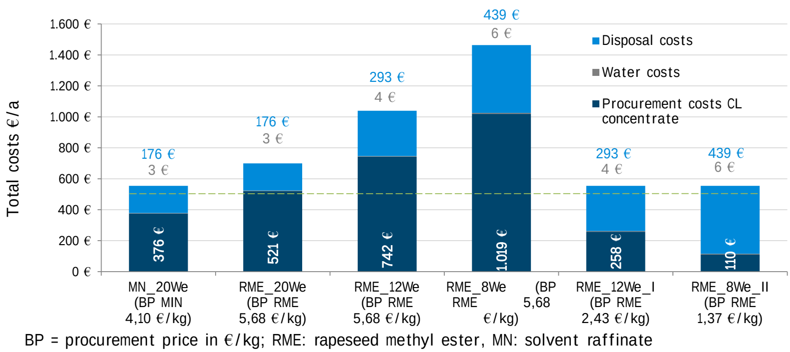

Figure 25: Total cost of CL variants per functional unit (FU) and year, broken down by cost item

The total cost for the base oil variant rapeseed methyl ester (RME_20Wo) is €699.49/a and is 1.3 times higher than the cost for the base oil variant solvent raffinate (MIN_20Wo) with a total cost of €554.60/a. With decreasing service life, the required amounts of cooling lubricant, water and disposal increase, so that the costs compared with the rape seed methyl ester variant with a service life of 20 weeks (RME_20Wo) increase by about 1.5 times (€1039.34/a) for a service life of twelve weeks and double with a service life of eight weeks (€1463.88/a).

With the same water and disposal costs, the procurement price for the variant rapeseed methyl ester with a service life of 12 weeks (RME_12Wo_I) or eight weeks (RME_8Wo_I) would have to be reduced to €1.97/kg or €0.61/kg of CL concentrate respectively to produce the same total cost of €554.60/a as the solvent raffinate (MIN_20Wo).

Conversely, the rapeseed-methyl-ester-based emulsion would require a lifetime of 26.5 weeks at a specific purchase price of €5.68/kg to achieve the same total annual cost as solvent raffinate (Figure 26).

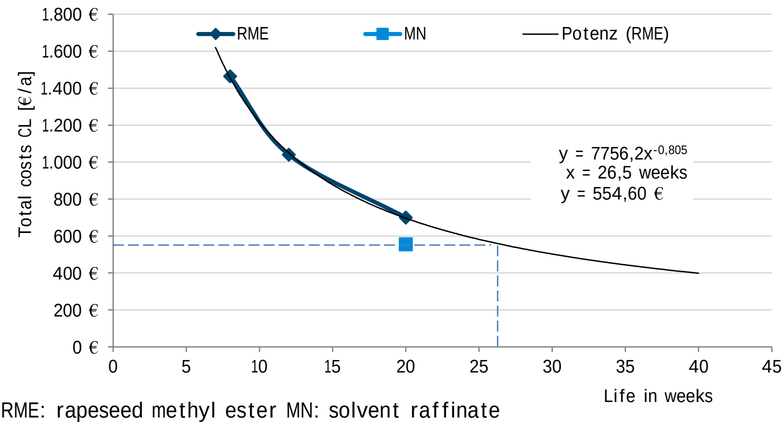

Figure 26: Break-even point of the base oil alternatives solvent raffinate and rapeseed methyl ester

Procurement costs account for the largest share of total costs with 68% for solvent raffinate (MIN_20Wo) and up to 74.5 % for rapeseed methyl ester (RME_20Wo). Water costs make up about 0.5 % each. The proportion of disposal costs is approximately 25% for rapeseed methyl ester (RME_20Wo) and up to 32 % for solvent raffinate (MIN_20Wo) (Table 12).

Table 12: Cost distribution of procurement, water, disposal

Variant	Cost proportion Procurement	Cost proportion Water	Disposal cost proportion
MIN_20Wo	67.79%	0.57%	31.64%
RME_20Wo	74.46%	0.45%	25.09%
RME_12Wo	71.43%	0.43%	28.14%
RME_8Wo	69.61%	0.42%	29.97%

In view of the overall costs for the CL alternatives, consideration of the use of a minimum quantity lubrication system or dry machining is recommended for CL users.

6 SUMMARY AND CONCLUSIONS

6.1 Summary of results

The aim of the study was to quantify the cost of materials, energy, water and land use over the life cycle of the CL, to show the use of supply-critical raw materials, to estimate the global warming potential in CO_2 equivalents and calculate the relevant costs for various base oil variants. For this purpose, the water-miscible cooling lubricant solvent raffinate with a service life of 20 weeks was compared with rapeseed methyl ester with a varying service life of 20 weeks, twelve weeks and eight weeks in a predetermined observation system (milling operation with CL circulation for production of 13,000 steel components per year (chapter 4).

The results of the study are summarised in Table 13 and classified into a scale system with "++" as the best and "- -" as the worst indicator value. Using the intermediate levels "+", "o" and "-", the relative performance of the alternatives in the scale system is expressed between the best and the worst indicator values.

Table 13: Overall comparison of the criteria for the base oil variants, based on the functional unit

Indicator	Solvent raffinate	Rapeseed methyl ester with service life		
		20 weeks	12 weeks	8 weeks
Cumulative energy demand	o	++	o	- -
Cumulative raw material consumption	++	+	-	- -
Water consumption	++	++	+	o
Land use	++	o	-	- -
CO_2 equivalent	o	++	o	- -
Total cost	++	+	-	- -

For all criteria, the results show a significant increase in expenditures, consumption, emissions and costs with decreasing service life of the rapeseed-methyl-ester-based CL emulsion. Within the considered use case, use of the rapeseed methyl ester as a base oil should be discouraged with a service life of any less than 20 weeks. A reduced service life of eight weeks for the rapeseed methyl ester variant results in the highest consumptions of raw materials, energy and water, as well as the highest CO_2 emissions and the largest land use. Thus, only the performance between the use of the base oil alternative solvent raffinate and rapeseed methyl ester with a service life of the CL emulsion of 20 weeks is worth considering in more detail.

From an ecological point of view, the results do not speak clearly in favour of the use of either of the two variants. While the use of rapeseed methyl ester causes less energy consumption over the entire life cycle, the use of solvent raffinate requires lower raw material consumption. In addition, the production, use and disposal of solvent raffinate hardly consume or use any water or land, whereas the parameter land use is more heavily in demand for rapeseed methyl ester. In turn, the emissions, expressed as CO_2 equivalents that are released throughout their life cycle cause a 30% larger environmental impact through the use of solvent raffinate.

The results of the evaluation of the raw material criticality of the fossil organic raw material crude oil and of the biotic raw material rapeseed (rapeseed oil) paint a clearer picture. For crude oil, dependency on international markets is considered critical, which is explained by high price volatility, rising demand and higher political country risk. For rapeseed, the ratio of reserves to global annual production shows critical values, but as a renewable raw material, it is rated less critically than crude oil.

From an economic point of view, the use of solvent raffinate is recommended for the application under consideration, since the procurement price, which accounts for the largest share of the total costs considered (over 68%), is more than one third cheaper than that of rapeseed methyl ester. However, this is just a snapshot that does not reflect supplier contracts, volume discounts and specific prices for speciality products. The prices for rapeseed methyl ester and for solvent raffinate can vary considerably. Under certain circumstances, such as a different product selection, the result may change in favour of the biotic water-miscible CL. In the case of a purchase decision, the CL user should check the stated service life of the CL because this has a significant impact on the economic balance sheet.

6.2 Conclusions

The results of this study show that, in addition to the conventional use of mineral-oil-based CL base oils, plant base oils (in the form of rapeseed methyl ester) with the same service life are an environmentally acceptable alternative.

In this study, a typical and frequently used, yet selectively specified process was chosen. In practice, the requirements for the process differ depending on the process type, component, precision and tolerance required, and the essential properties that the cooling lubricant must have. In this context, the user always has to decide situationally how the CL is to be formulated and put together. Depending on the application and requirement profile, non-water-miscible CL and viscous water-based, mineral-oil-free CL may also be considered. As a rule, many years of practical experience are required to ensure successful use of these techniques for the specific application in question.

Based on the results of this study, metal-cutting machining SMEs are advised to consider the use of plant-based CL instead of mineral-oil-based CL in view of certain environmental and cost aspects. Especially for small companies, further input by means of competent support and experience from the supplier, formulator, dealer and associations is required.

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APPENDIX A

Table 14: Waste quantities for water-mixed and non-water-miscible CL[120]

AVV no.	Description	2011	2012	2013	2014
Non-water-miscible CL in tonnes					
120106*	Mineral-oil-based machining oils containing halogens (except emulsions and solutions)	200 t	200 t	200 t	300 t
120107*	Halogen-free mineral-oil-based machining oils (except emulsions and solutions)	71,400 t	58,000 t	56,000 t	55,700 t
120110*	Synthetic machining oils	1,100 t	800 t	800 t	800 t
120119*	Easily biodegradable machining oils	0 t	0 t	0 t	0 t
Total non-water-miscible CL		72,700 t	59,000 t	57,000 t	56,800 t
Water-mixed KS in tonnes					
120108*	Halogen-containing machining emulsions and solutions	300 t	300 t	400 t	700 t
120109*	Halogen-free processing emulsions and solutions	644,700 t	672,300 t	721,700 t	733,500 t
Total water-mixed CL		645,000 t	672,600 t	722,100 t	734,200 t
Overall total		**717,700 t**	**731,600 t**	**779,100 t**	**791,000 t**
% non-water-miscible CL		**10.1%**	**8.1%**	**7.3%**	**7.2%**
% water-mixed CL		**89.9%**	**91.9%**	**92.7%**	**92.8%**

Table 15: Domestic deliveries of water-miscible (wmb) CL and non-water-miscible (nwmb) CL (2004-2015) [121]

	2015	2014	2013	2012	2011	2010
wmb CL	21,099	17,025	17,597	18,920	20,208	27,548
nwmb CL	28,779	27,365	27,238	26,945	25,494	42,148
Total	49,878	44,390	44,835	45,865	45,702	69,696
% wmb CL	42%	38%	39%	41%	44%	40%
% nwmb CL	58%	62%	61%	59%	56%	60%
	2009	2008	2007	2006	2005	2004
wmb CL	17,250	27,407	30,776	29,482	30,607	27,010
nwmb CL	24,779	38,370	41,532	38,339	45,094	46,846
Total	42,029	65,777	72,308	67,821	75,701	73,856
% wmb CL	41%	42%	43%	43%	40%	37%
% nwmb CL	59%	58%	57%	57%	60%	63%

[120] See Statistisches Bundesamt (2013) – (2015a).

[121] See Federal Office of Economics and Export Control (2015).

APPENDIX B

Table 16: Interviews on base oil alternatives for CL emulsions I

Question	Answer	Interview type and date
Survey of CL manufacturers, CL formulators, associations and authorities		
• Are vegetable or animal oils and substances used as alternatives to mineral oil for CL base oils? • If so, which ones?	• Vegetable or animal oils and substances are used n in synthetic form, e.g. as rapeseed methyl ester. These oils and substances are more commonly used as additives in smaller quantities. • The animal materials used are predominantly esterified tallow fatty acids or lard oil.	phone, February 2016
	• The use of rapeseed methyl ester predominates in Germany. Rapeseed can also be substituted by synthetic esters of palm or coconut oil. • However, synthetic oils based on palm oils are mainly used as an additive. As a base oil, they are too expensive and too valuable. • Animal fat and used cooking oil as base oil tend not to be accepted by users.	phone, February 2016
	• The use of animal oils and substances has tended to decline as a result of the BSE crisis and religious restrictions, as CL 'kosher' or 'Halal' certification is comparatively too costly. • In the case of vegetable oils, the use of rapeseed methyl ester predominates, and they are often included in the formulation to a lesser extent.	phone, February 2016
	• Mainly mineral oil is used. Plant and animal base oils have hardly any influence so far.	phone, February 2016
	• In the choice of alternatives, rapeseed-oil-based ester has an edge over palm-oil-based ester, in that rapeseed oil is preferable from a future perspective for several reasons. Rapeseed oil is mainly grown in Germany and the EU; fallow land is still available in the EU. The main cultivation areas for palm oil are Indonesia and Malaysia, South America and Africa. On the one hand, further use of palm oil against the background of deforestation of the tropical rainforest is questionable. On the other hand, it makes Germany even more reliant on imports for its procurement of raw materials. Rapeseed oil cultivation, by contrast, would strengthen the regional economy.	E-mail, then by phone, 05.02./ 10.2.2016
	• Vegetable and animal fats (unesterified) are unsuitable (hard to emulsify, not as biodegradable, prone to deposits and sticking, often incompatible with gaskets and coatings, etc.)	E-mail, 04.02./ 05.02.2016

Table 17: Interviews on base oil alternatives for CL emulsions II

Question	Answer	Interview type and date
Survey of CL manufacturers, CL formulators, associations and authorities		
• Are PAOs suitable for use in wmb CL? • How important are they in practice? • For which specific applications are they preferred and in what quantities?	• PAOs make wmb CL even more expensive than it already is. • Solution behaviour is not good enough. • Use is estimated to be virtually non-existent.	phone, 01.07.2016
	• PAOs are only used for MQL due to their price; additives are needed to make them wmb; no wmb CL in our own portfolio with a PAO base; use of polyglycol.	phone, 04.07.2016
	• PAOs are used in wmb CL, sometimes up to a proportion of 50%, depending on the requirements of the user: when a high level of power is needed with a long service life, especially in the grinding industry.	phone, 01.07.2016
	• PAO-based lubricants are used at maximum for special applications in small tonnages, e.g. grinding applications; mineral oil-based CLs are better suited because of their polarity and price; no PAO is used for our own wmb CL.	phone, 04.07.2016
	• PAO is so expensive that the cost of raw materials would be too high; formulator has not yet produced wmb CL on PAO basis; although this has positive properties (including biodegradability), they are offset by the price. PAOs are certainly used in greases and oil formulations, but they have hardly any significance in the chip removal area.	phone, 04.07.2016
	• Since 2012 Castrol has offered wmb CL on PAO basis (Castrol Syntilo 75 EF), which is suitable for grinding, turning and milling	E-mail, then by phone, 17.05./19.05.2016
	• GTL base oils are being tested; PAO is too expensive as a base oil. On the production side and also in special applications, a decline can be seen.	phone, 01.07.2016
	• PAO is not used in wmb CL; only in nwmb CL like lubricating oils. Special properties of PAO such as thermostability and viscosity index are of no importance in wmb CL, as these properties are achieved via the water; in special application, in which e.g. evaporation occurs at the processing site, PAO may be beneficial.	phone, 04.07.2016
	• PAO is used in CL only for nwmb CL, but not for wmb; PAOs have positive properties such as better air separation capacity and higher viscosity index of 10 - 30 Ns/m^2, but the product price is too expensive.	phone, 04.07.2016
	• The positive properties of PAOs do not stand out when used as a base oil in wmb CL as a result of the strong dilution; they are too expensive for that	phone, 04.07.2016

Table 18: Interviews on prices for base oils and base oil components

Question	Answer	Interview type and date
Survey of CL manufacturers, CL formulators, associations and authorities		
• What are the prices (data sources) for base oil components?	• Current daily prices for naphthenic mineral oil in purchasing are around 95 cents/kg. • PAOs are not used for wmb CL because they are more expensive than regular mineral oils and they do not bring any benefits to wmb CL. He could not name more exact prices for PAOs. • Manufacturer does not use RME because of a lack of water resistance, but another re-esterified rapeseed oil, which costs about €2/l.	E-mail contact form and mail exchange/10.05./ 11.05.2016
	• For such special crude oil intermediate products, no prices or price indices are known.	phone, 09.05.2016
	• The following plausibility consideration: In commercial hydraulic oils, which are also used for various purposes as multifunctional oils, the kg price is an average of about €1.00. This finished product consists of 95 - 99% of a mineral oil cut as a base oil, which is comparable to that of the solvent raffinate	E-mail, then by phone, 04.05./17.05.2016
	• No prices or price indices are known for crude oil intermediate products of this sort.	phone, 09.05.2016
	• No prices or price indices are known for crude oil intermediate products of this sort.	E-mail, then by phone, 04.05.2016
• What are the prices for RME base oil components?	• Since there is no reason for the price of RME on the biofuels market (main application) to differ from that on the small niche markets other than use for biodiesel, since the product must meet the same certified characteristics for both applications, it can be assumed that €0.70/l (source: Burghardt 2015) is also the average price that CL formulators pay for RME as a base oil.	by phone, then e-mail, 18.05./19.05.2016

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Im Auftrag des:
Bundesministerium
für Umwelt, Naturschutz,
Bau und Reaktorsicherheit

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