



Life Cycle Assessment – Example 1

Why has this study been selected as an example?

The requirements of the Life Cycle Assessment method provided by the ISO/DIN 14040 et seq. standards are sometimes difficult to understand. The study “*Life Cycle Assessment of selected raw materials for paints: a comparison between vehicles based on renewable and petrochemical raw materials*” [1] was chosen to make the abstract statements of this norm more clearly. The study was carried out according to the ISO standard. Differently from this, the parts “Life Cycle Impact Assessment” as well as “critical review” were not included into the balance. Nevertheless, the necessary steps the Life Cycle Assessment method (without Impact Assessment) can be conceived within this example.

Background of the study

The usage of renewable resources [see also “Renewable Resources”, glossary] will become more important in future. For being competitive, products made by refining these renewable resources have to be technically and economically equal to products made from petrochemical raw materials. In addition, they have to be more sustainable.

The study contains a comparison of the environmental impacts of petrochemical coating binders for wood and wooden materials with binding agents based on renewable resources. With it the competitiveness should be checked from the ecological point of view.

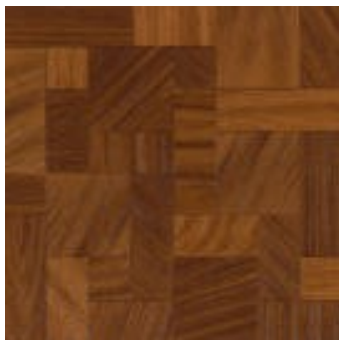


Fig. 1: parquet surface, sealed with UV-hardening varnishes



How were the general conditions defined?

The Aim of this Study

The aim of the study was a holistic data entry of environmental impacts caused by the production of the coating binder *linseed oil epoxide* (Leinöleoxid, ELO) on the basis of the renewable material linseed oil. A petrochemical coating binder consisting of a mixture (50:50) of *tripropylene glycol diacrylate* (TPGDA) and *bisphenol A diglycidyl ether acrylate* (DGEABA) has been taken as reference.

The selected Function or Functional Unit

The manufacturing of the alternative binding agents was examined as function. The application properties of the alternative binding agents (e. g. reactivity, scratch resistance, adhesion and resistance to acetone) are considered to be equal and thus they can be applied in the same scope. One ton of the processible coating binder was defined as functional unit. That means that all energy and material flows have to be recorded and entered into the balance sheet which are concerning with the production of this functional unit.

The System boundaries of the Investigation

According to the aim of a holistic examination all up- and downstream processes were considered. That means that the non-facility scopes of supplying raw materials and energy were also included in the examination. The material and energy flows emerging within the system boundaries were observed and inventoried usually from their withdrawal or to their releasing into the environment respectively. The environment serves as source (e. g. the removal of crude oil from the deposits) or as drain (e. g. CO₂-emissions into the atmosphere) for material flows. The system boundary is defined as the gate of the manufacturer of the processible coating binder. The system boundary “gate” could be chosen because technical equivalence was assumed for the different products. That means there is no difference in usage, disposal etc.

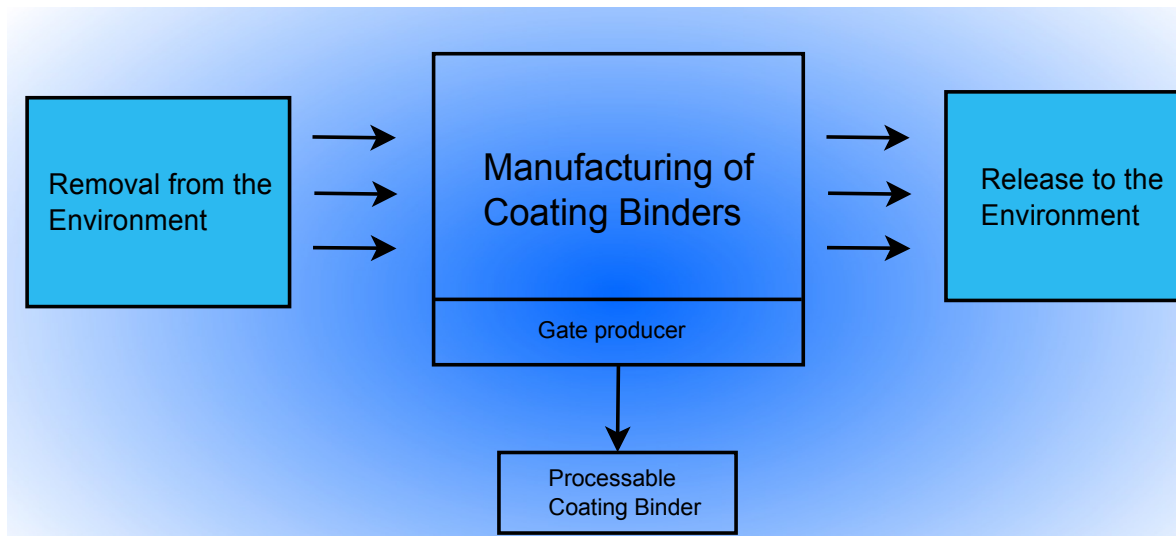


Fig. 2: System of Coating Binders

Other predefinitions must be determined for selecting the inventory boundaries. They are described subsequently.

Cut-off Criteria (Limits of detail)

No material flows were usually cut off in the presented study. All flows required for the interpretation have been observed and evaluated from entering to leaving the system boundaries if the database was sufficient.

Allocation

The total process energy was allocated according to the proportion of the particular product in the total production. The emissions and disposals that result from the manufacturing were treated as well. They were prorated according to their share in the entire output, too.

Credit items

Within the study it was considered that intermediates are not produced in any affiliated location and that there is no usage of the waste heat. Credits were only considered for the production of acrylic acid because of the good database. There was also no bonus passed to the inventory's credit for the usage or the utilization of coupling products, but the possibility was pointed out.

Geographical and chronological reference



The considerations refer to the political borders of the Federal Republic of Germany. If substances were provided in other countries (e. g. mineral oil) the country of origin has been chosen as reference weighed according to the particular market share of the substance in Germany. The year 1999 was selected as reference year for the views.

How was the Inventory Analysis drawn up?

In the following paragraph the details of drawing up an inventory analysis should be described more precisely. The time scope and the demands on the amounts of data could be demonstrated by it.

The structure of the system was refined because of the fact that two different ways of manufacturing are compared to each other and those methods consist of varying steps. This procedure is explained in the following

Fine Structure of the System

The system boundaries have been divided into the sectors “*Linseed oil epoxide*” and “*Petrochemical coating binder*” for drawing a comparison. Additional subdivisions depend on the logical order of the value-added chain of each system. The inventory section “Linseed Oil Epoxide” was subdivided into the sub-processes shown in Figure 3 according to the chain of economic value added.

Within the system “Linseed oil epoxide” a sensitivity analysis was performed in the step “Oil production / refining”. A central as well as a peripheral oil extraction was examined here.

The system “Petrochemical coating binder” was also subdivided concerning the way of production. This results in the division shown in Figure 4.

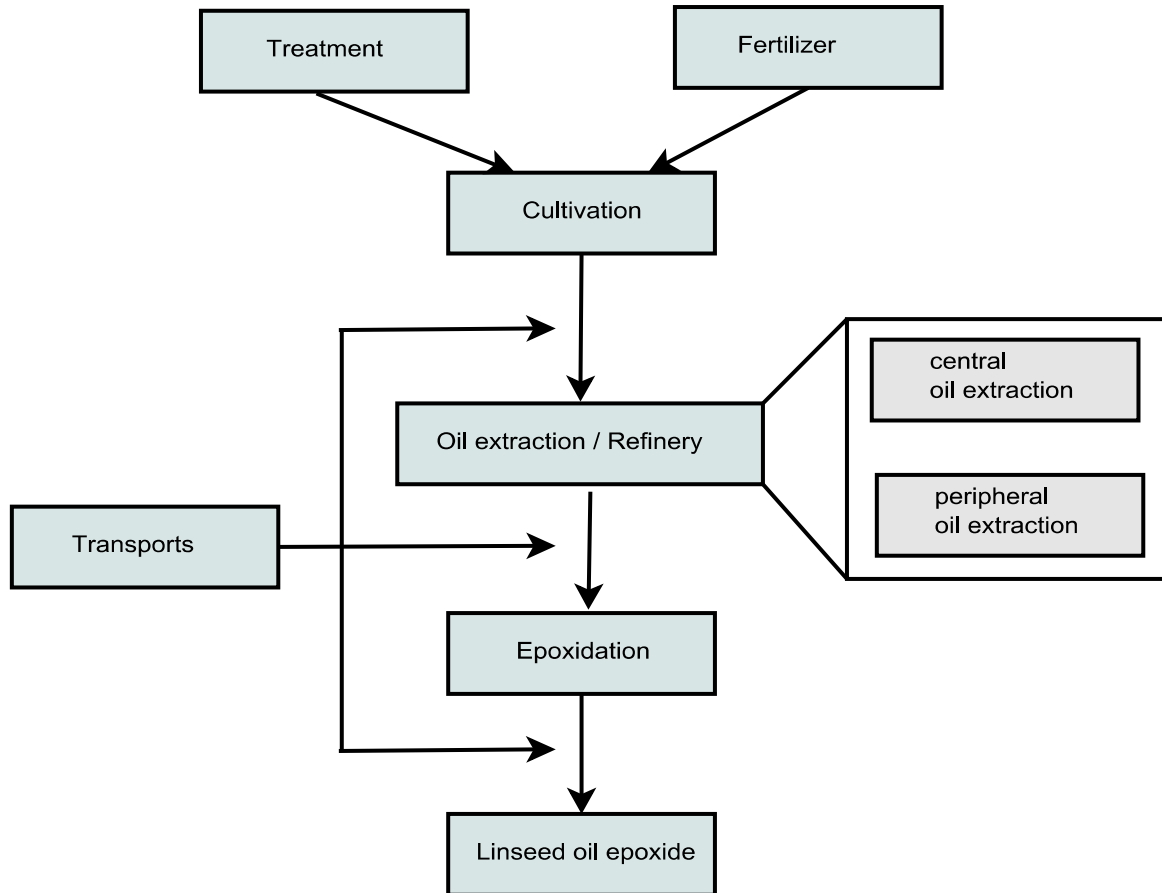


Fig. 3: Structure of the System "Linseed Oil Epoxide"

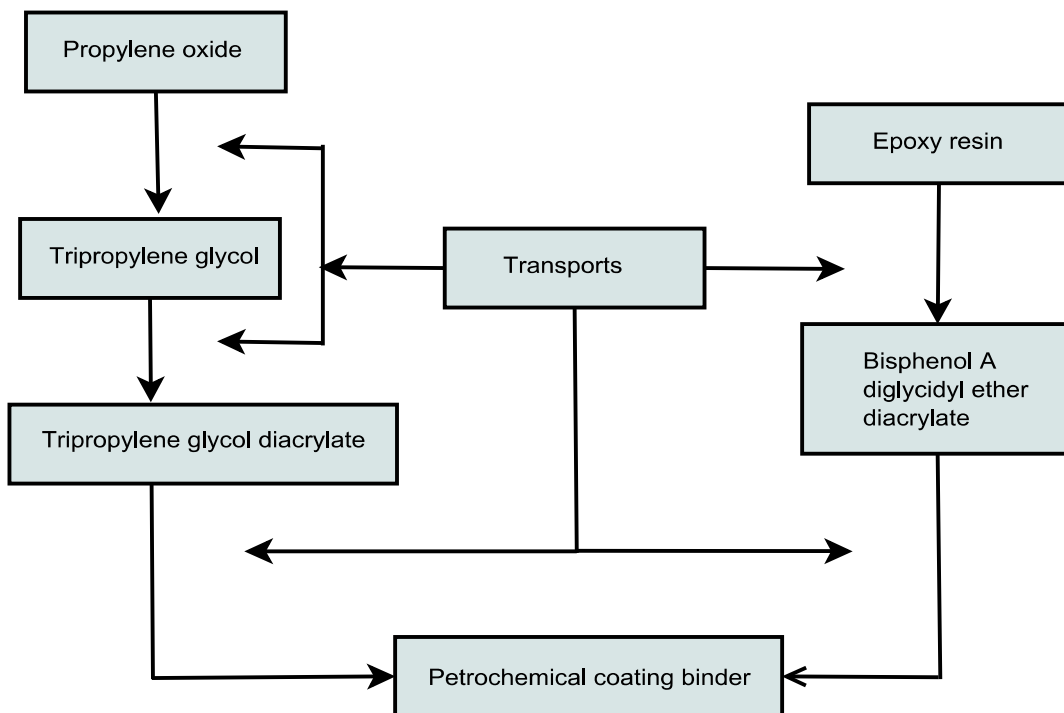


Fig. 4 : Structure of the System "Petrochemical coating binder"



Examples for Partial Processes

The implementation of an inventory analysis for the sub-process “Propylene oxide” is explained in more detail to demonstrate the procedure of evaluation. The production of propylene oxide by chlorohydrin-synthesis has to be considered on this occasion. Propylene produced from the cracking process of mineral oil is converted into propylene oxide (PO) during the chlorohydrin synthesis. Propylene and chlorine gas first react to chloropropanol and other intermediates. Chloropropanol is passed to a saponifier and is converted to PO with calcium hydroxide in the second step. Calcium hydroxide produced as a coupling product is released into a discharge system together with the waste water. The energy needed for the reaction is fed in form of steam. Alternative processes were developed to synthesize propylene oxide because of the large salt load among other things. However, the chlorohydrin procedure is still most widespread in Germany.

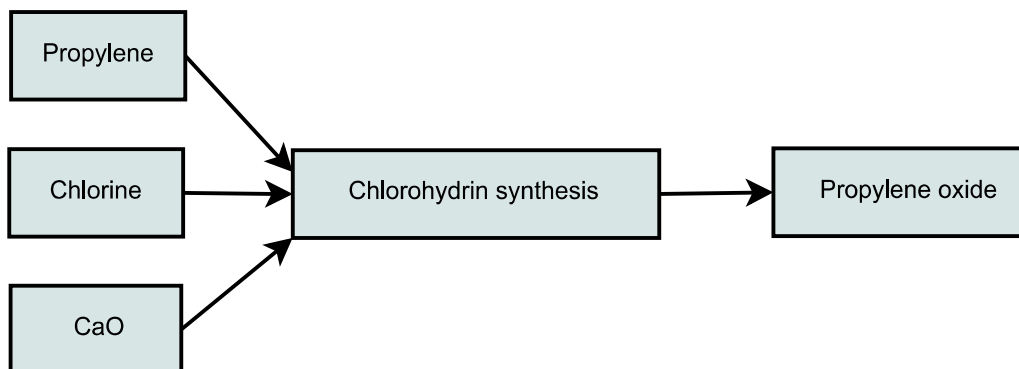


Fig. 5: Reactants of the chlorohydrin synthesis

The reactants of the chlorohydrin-synthesis have already been produced in other processes. Thus, they are preliminary chains of the production of propylene oxide.

Preliminary Chain of Propylene

The production of propylene was inventoried from the removal of the raw materials off the natural resources including the processes involved. The oil production was followed by the purification and workup in the refinery. In this process the crude oil is fragmented into different fractions (heavy fuel oil, benzene, various distillates of medium boiling points, liquefied gases, naphtha and refinery gases) by fractionated distillation. The naphtha fraction (boiling points between 65 °C and 200 °C) was worked up in the steam-cracker afterwards. For this purpose the fraction is heated with steam in several steps from 500-650 °C to 750-875 °C. Main components of the process are ethylene, propylene, butane as well as other olefins and diolefins which lead to a cleavage of larger molecules. Undesired by-products



and reverse reactions are avoided by cooling down the gases quickly and washing them with water. Propylene can finally be separated from the resulting gas mixture.

Preliminary Chain of Chlorine

The production of chlorine was inventoried including the removal of the raw materials from the natural resources and the processes involved. The most important procedure to produce chlorine is the Chloroalkali-Electrolysis with the three alternative processes: Amalgam-Process, Diaphragm-Process and Membrane-Process. All processes have the electrolysis of a sodium chloride-solution with the production of hydrogen, chlorine and sodium hydroxide at the same time in common. The electrolysis of the Amalgam-Process takes place in a mercury cell with a titanium or graphite anode and a mercury cathode. At the anode gaseous chlorine is formed while sodium reacts with mercury and is whetted as amalgam from the cathode. Sodium reacts with water at a catalyst surface (graphite) in a decomposer for amalgam to hydrogen and sodium hydroxide.

The spaces of the cathode and the anode are separated by a diaphragm in the Diaphragm-Process. The sodium chloride solution reacts to chlorine in the anode space, passes through the diaphragm and forms hydrogen or sodium hydroxide respectively at the cathode. A mixture of hydrogen and chlorine is circumvented by the diaphragm. Thus a workup of the products is easier afterwards.

In the Membrane-Process the spaces of the anode and the cathode are kept apart by a membrane which is waterproof but penetrable for ions. The solution of sodium chloride reacts to chlorine in the anode space whereas water is decomposed to hydrogen and hydroxide in the cathode space. The sodium ions diffuse through the membrane into the cathode space where it is isolated as sodium hydroxide. The allocation of the multi product system Chloroalkali-Electrolysis was carried out according to the principles described before.

Calcium hydroxide

Limestone has to be burned to produce calcium hydroxide. In a second step the formed calcium oxide is slaked with water to receive calcium hydroxide. Limestone is surface mined. For this purpose the first layer of earth is carried off and afterwards the limestone is mined with adequate quarry machines. The process of lime burning is to be understood as pyrolysis of the limestone: $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$. The pyrolysis is technically carried out at 900-1100 °C. The burning of the lime can take place in different reactors. In the study the lime burning is inventoried in a rotary furnace which is heated with mineral coal demanding an energy of 5200 MJ/t quicklime. Per ton of lumpy quick lime 1755 kg of limestone are required. A current of about 130 MJ/t quicklime is needed beside the demand for mineral coal. In the process of burning lime CO_2 emissions have to be inventoried as process-related emissions that occur during the so-called deacidification of lime. The limestone to feed the



furnace consists of 767 kg bound carbon dioxide from which 755 kg/t quicklime are released during the burning process. A dust amount of 0.17 kg/t quicklime is assumed to emerge during the burning process.

Steam

The energy required for the production of PO is provided in form of steam with 40-60 bar. One ton of steam is equivalent to a primary energy of 3150 MJ. This energy is generated by a mixture consisting of 31.1 % coal, 4.1 % fuel oil EL, 18.3 % fuel oil S and 46.5 % natural gas.

What is the procedure of gathering the data?

The relevant material and energy flows of the required processes were collected in order to perform the inventory analysis. The process-specific in- and output data were derived and worked up. Afterwards the results of the inventory analysis were registered or calculated respectively. The preconditions which were defined in the paragraph “Aim and System boundary of the Investigation” have been always kept to or they have been adapted to the necessities of the inventory analysis. The following figure (Fig. 6) exemplifies the input/output of the chlorohydrin synthesis:

| Input / Output | | | | | Constraints | | | | |
|----------------|-------|-------------------|----|-------------|-------------|--------|-------------------------------|----|-------------|
| Var | Place | Material | DQ | Coefficient | Var | Pla... | Material | DQ | Coefficient |
| X01 | P21 | ▲ Propen | ● | 10400.00 | Y02 | P2 | ▲ Dichlorpropan | ● | 1450.00 |
| X02 | P5 | ▲ Chlor | ● | 18000.00 | Y03 | P26 | ▲ 2,2-Dichlordiisopropylether | ● | 250.00 |
| X04 | P25 | ▲ Dampf | ● | 21400.00 | Y04 | P26 | ▲ Diol | ● | 100.00 |
| X05 | P8 | ▲ Brandkalk (CaO) | ● | 15700.00 | Y05 | P29 | ▲ Propylenoxid | ● | 12700.00 |
| X06 | P19 | ▲ Wasser, unspez. | ● | 496000.00 | Y06 | P17 | ▲ Kohlendioxid, fossil (L) | ● | 200.00 |
| | | | | | Y08 | P17 | ▲ Calciumchlorid (CaCl2) (w) | ● | 26000.00 |
| | | | | | Y10 | P17 | ▲ Diol | ● | 650.00 |
| | | | | | Y11 | P17 | ▲ Dichlorpropan | ● | 160.00 |
| | | | | | Y12 | P17 | ▲ 2,2-Dichlordiisopropylether | ● | 120.00 |
| | | | | | Y14 | P17 | ▲ Abwasser (Prozess) | ● | 518000.00 |
| | | | | | Y15 | P17 | ▲ Calciumhydroxid (w) | ● | 1700.00 |
| | | | | | Y16 | P17 | ▲ Propylenoxid (w) | ● | 80.00 |

Fig. 6: Input/Output – Chlorohydrin synthesis for the production of propylene Oxide

The proportions of the particular substances are given in the shown input/output inventory. Therefore the mass unit can be chosen freely. After the drawing up of the inventory analysis the evaluation was carried out based on the results of the inventory analysis.



Evaluation

As described before no impact analysis was carried out in the inventory discussed here. Merely four parameters of the inventory analysis were consulted for the comparison between the two ways of manufacturing both paints relating to their environmental impact. Because of this procedure no absolute results could be acquired from the inventory. However, such an approach admits to determine existing tendencies and to point out potential improvements. In the evaluation the particular process steps within the system boundaries were compared as well as both products. The following categories were taken into account:

- Cumulated energy demand (abbr.: CED, German: KEA)
- Carbon dioxide emissions (CO₂)
- Nitrogen oxide emissions (NO_x)
- Resource consumption (energy sources)

The emissions of carbon dioxide and nitrogen oxide as well as the consumption of non-generative energy sources are mainly coupled to the generation and consumption of energy. Against this background only the results of the Cumulated Energy Demand (CED) are presented in this summary. The Cumulated Energy Demand states the entirety of the primary energy demand that results from the production, usage and disposal of a product or can be causally allocated to it respectively.

Cumulated Energy Demand – System “Linseed Oil Epoxide”

The different process components of manufacturing epoxidized linseed oil were inventoried. The divided CED values of the inventory analysis (CED fossil, CED hydropower, CED nuclear, CED unspecified) were summed up as CED total.

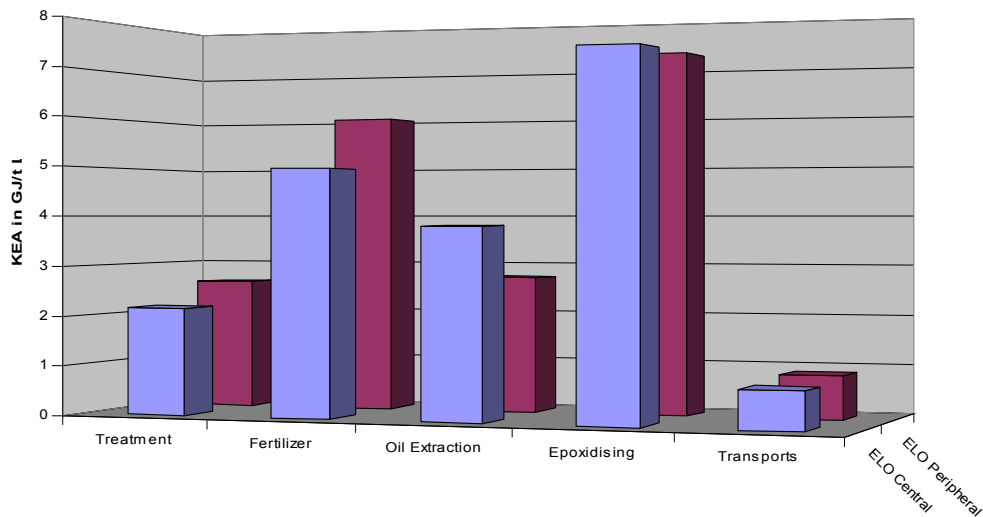


Fig. 7: CED – System “Linseed Oil Epoxide”

The process step “Transports” includes all transport intervals disclosed in the material flow sheet. The transport of fertilizers is assigned to the sector “Fertilizers” however. The graphical presentation (Fig. 7) offers the following scene for both scenarios:

The values of the Cumulated Energy Demand in the scenario “Decentralised Processing” are lying slightly above the CED values of the “Central Processing” as well as the process step “Fertilizers”. These differences are caused by the method of extracting the oil. The oil recovery runs without an extraction step in the scenario “Decentralised Processing”. The degree of removed oil has a value of 81 %. Thus, about 76 kg oil per ton seed remain in the linseed cake. That is why more seed is to be cultivated to produce the required amount of crude linseed oil for the further processing and consequently more energy is needed.

The higher energy demand in the decentralised extraction of oil can be affirmed with an extraction step which requires thermal energy. The step of the extraction is missing in the scenario “Decentralised Processing” as mentioned above. Also the transport processes are varying in their energy demand. This can be explained with the fact that the assumed proportion of the inland water transportation is very high for the subsequent treatment of the



seed in a central oil mill, whereas the linseed oil extracted by a local oil mill is dispatched via roads.

Cumulated Energy Demand – System “Petrochemical Coating Binder”

According to the treatment of the system “Linseed Oil Epoxide” the different kinds of Cumulated Energy Demand are also summed up in CED total (Fig. 8). The transport intervals summarised in the process section “Transports” correspond to the conveyance processes disclosed in the material flow sheet. The process sections “Tripropylene glycol diacrylate (TPGDA)” and “Bisphenol A diglycidyl ether acrylate (DGEABA)” include the energy credit from the production of acrylic acid already.

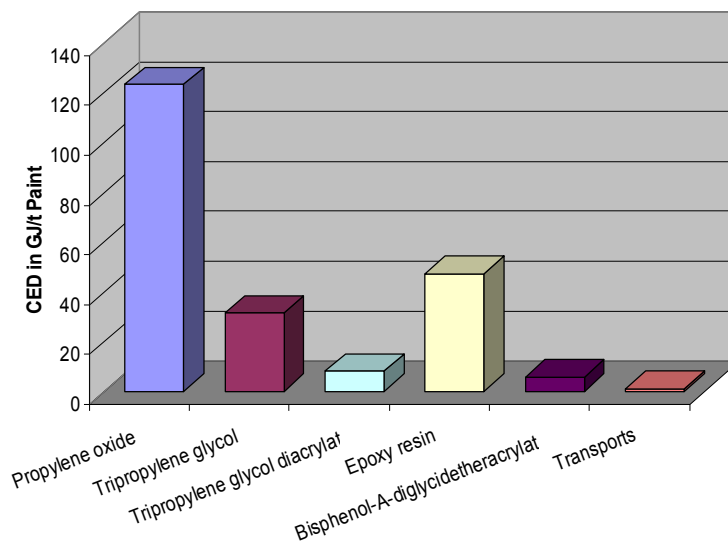


Fig. 8: CED – System “Petrochemical Coating Binder”

The energy demand for the production of tripropylene glycol diacrylat is determined by the manufacturing of propylene oxide. The total energy demand for producing one ton of processible paint is also dominated by the high CED values of the production of propylene oxide as well. Very high energy quantities have to be provided especially for the manufacturing of the preliminary products propylene and chlorine. The values of the Cumulated Energy Demand of the PO-production were set side by side for illustrating (Fig. 9).

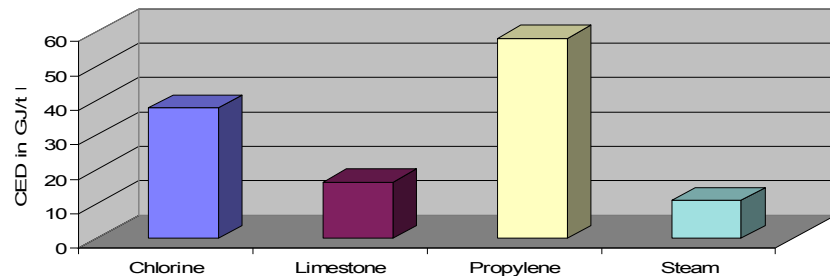


Fig. 9: CED – Production of Propylene Oxide

The production of tripropylene glycol shows a high energy demand, too. This can be attributed to the huge surplus of water. Large energy quantities are required to transfer water into the gas phase and to provide the necessary pressure for the reaction.

The manufacturing of TPGDA is a process section which consumes about 8 GJ which is small compared to the total energy quantity of the paint production. Among other things this value results from the credit item which arises from the production of acrylic acid. Per ton of acrylic acid 18.8 GJ of thermal energy were credited in this process which is forwarded to other consumers and offers the saving of primary energy sources.

DGEBA is synthesised in several steps which are all summed up in the process section “Epoxy Resin”. This is another energy-intensive production step beyond the production of propylene oxide.

The manufacturing of DGEABA from epoxy resin takes place under the same reaction conditions as the production of TPGDA. Acrylic acid is employed here as well and the thermal energy resulting from the production of the acrylic acid can be credited to the process. This credit leads to a low energy consumption of the sub-process in comparison to the total energy demand during the production of the coating binder.

Transport processes are apparently no relevant factor regarding the Cumulated Energy Demand of the petrochemical paint. Nevertheless they contribute to high overall energy



consumption.

Cumulated Energy Demand – Comparison of the System Boundaries

In the final evaluation of the Cumulated Energy Demand the different system boundaries were contrasted to each other (Fig. 10). Thereby the total CED value of the petrochemical paint is significantly higher than the CED values of the ELO.

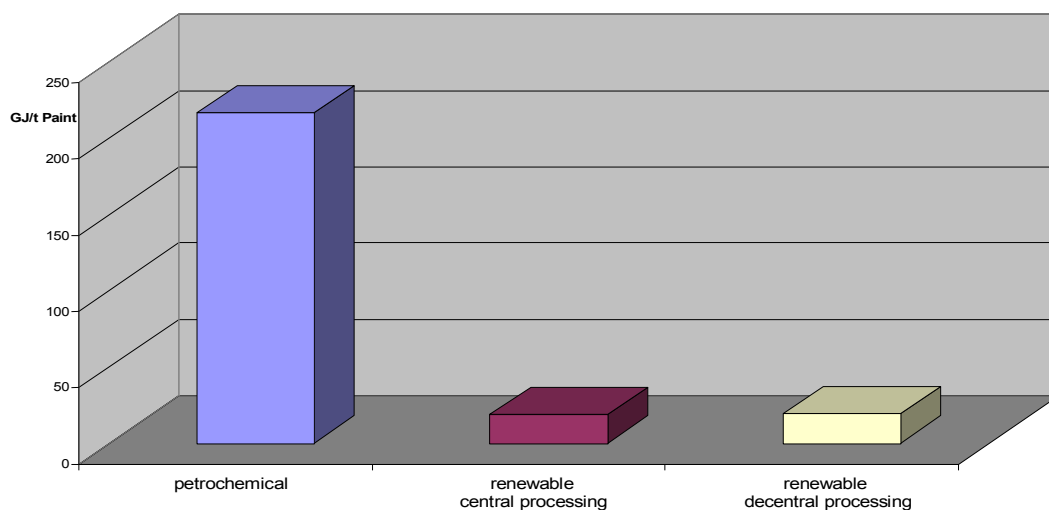


Fig. 10: CED – Comparison of the system boundaries

Discussion

The results of the comparison demonstrate that an employment of linseed oil epoxide as UV-hardening paint is beneficial according to the given boundary conditions and evaluated categories. However, the results should not be regarded as absolutely and definitely. The study falls back on literary data and manufacturer information as well as it includes own calculations and estimates as it is usual in Life Cycle Inventories. Against this background a wider error range of the results is possible. A modification of the boundary conditions may lead to other results. Thus, innovations in the synthesis of petrochemical coating binders could be followed by strong improvements of the values of this system. Replacing the production of propylene oxide by a less energy and substance consuming procedure could already reduce the environmental impact of the petrochemical coating binders significantly. The reuse of the waste heat resulting from sub-processes in affiliated locations would also lead to a reduction of emissions and resource consumption. But under the given conditions the differences are so



obvious that it is unlikely to reverse the described advantages into their opposite.

As could be shown by this study, renewable resources are all the more advantageously as the petrochemical competitive product is more complex or more steps of synthesis are required for its production respectively. This becomes very clearly when a plant provides a chemically challenging, “highly ennobled” product. The “chemical” usage of biological products should take ecological priority over a thermal usage as revealed in this study. The primary energy which is saved on the industrial assignment of renewable resources seems to be higher than the energy provided by using renewable resources as energy plants.

The premise for the advantages of using renewable resources is a fruitful plant with a high yield of the desired substance compared to the acreage. The advantage of renewable resources is reduced or reversed by low yields per area under cultivation. In conclusion the expenses are very important as well as the number of work steps for the manufacturing of a substance.

- [1] Bartmann, D., Peters, H., Lott, A., Sack, W., Metzger, J.O., Diehlmann, A., Kreisel, G. 2000. *Strahlenpolymerisierbare lösemittelfreie Schutz- und Dekorationsbeschichtungen für Holz und Holzwerkstoffe auf Basis nachwachsender heimischer Rohstoffe*. DBU-Az. 08150.