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Environmental impacts and energy balances of wood products and major substitutes

LCA of single-family houses

Definition of houses

This section deals with family houses in Central Europe and demonstrates the influence of different construction types and material mixes on the environmental impacts. It is well known that building styles worldwide differ from each other and even in Europe there are considerable differences (form, size, material mix) in standard family houses. To illustrate the impact of material selection, the following house types were investigated:

• Timber-frame house: Timber-frame house is made of wood, wood-based materials and mineral-based materials. The share of wood and wood-based materials is relatively high.

• Blockhouse: Blockhouse is made of wood and wood-based materials. The share of mineral-based materials is extremely low.

• Brick house: Brick house is made predominantly of mineral-based building materials. The use of wood and wood-based materials is at the normal level[4] for Central Europe.

According to the Damberger study (1995), the average lifetime for the three house types is 80 years.

As can be seen from Tables 2, 3 and 4, the input of building materials for the raw construction of these houses differ from each other. However, in order to simplify the comparison, it is assumed that the installations for water, electricity, etc., are the same for the three house types. The background data for LCI were collected from BM-BAU report (1993), Damberger study (1995) and Scharai-Rad and Welling (1999).

Life cycle inventory for single-family houses

The figures in Tables 2, 3 and 4 indicate LCI for the timber-frame house, blockhouse and brick house. The building materials necessary for the construction of the houses concerned amount to 131 tonnes/unit, 170 tonnes/unit and 207 tonnes/unit, respectively. Considering that for cellar construction a constant amount of 0.66 tonnes/m² of concrete is used, the real differences in input of building materials can be found in the part above the ground. The material input for this portion of the constructions is 117 tonnes/unit for a timber-frame house, 59 tonnes/unit for blockhouse and 41 tonnes/unit for brick house. The main difference is also in the share of wood and wood-based materials that are renewable and can be utilized after use as waste wood for energy generation.

Tables 2, 3 and 4 show that the energy inputs amount to 41 100 kWh for the brick house and 34 250 kWh/unit for the timber-frame house as well as for the blockhouse which, therefore, demonstrate that energy consumption for the brick house is far above that for other houses. On the other hand, both the timber-frame house and the blockhouse contain much more renewable materials that can be utilized as CO_2-neutral fuel resulting in a decline of net energy consumption and related emissions (see next section "Life cycle impact assessment") and an increase in the volume of wood-based building materials.

Table 2: Energy and material inputs for construction of a single-family house based on the timber frame construction technique

INPUT	OUTPUT
Building materials	**One timber-frame house**

(tonnes/timber-frame house)		**(m²)**	
Roof tiles, concrete	6.10	**Covered area**	**79.46**
Windows, glass doors	0.45	Layout first floor	70.23
Gypsum	3.10	Layout second floor	65.95
Gypsum fibreboard	16.30	**Layout total**	**136.18**
Wood	12.10		
Filler	0.10		
Mineral wool	1.20		
PE foil	0.11		
Expandable polystyrene	0.27		
Finish	0.28		
Particle board	0.86		
Fasteners steel	0.55		
Concrete for cellar	90.00		
Total without cellar	**41.00**		
Total with cellar	**131.00**		
Energy (kWh/unit)	**34 250.00**		

Table 3: Energy and material inputs for construction of a single-family blockhouse

INPUT		**OUTPUT**	
Building materials **(tonnes/blockhouse)**		**One blockhouse** **(m²)**	
Concrete roof shingles	6.80	**Covered area**	**97.43**
Windows, glass doors	0.68	Layout first floor	85.38
Gypsum fibreboard	5.30	Layout second floor	84.64
Wood	42.90	**Layout total**	**170.02**
Mineral wool	1.00		
PE foil	1.14		
Expandable polystyrene	0.18		
Particle board	0.95		
Fasteners steel	0.55		
Concrete for cellar	111.00		
Total without cellar	**59.00**		
Total with cellar	**170.00**		
Energy (kWh/unit)	**34 250.00**		

Table 4: Energy and material inputs for construction of a single-family brick house

INPUT		**OUTPUT**	
Building materials **(tonnes/brick house)**		**One brick house** **(m²)**	
Concrete	19.80	**Covered area**	**79.46**
Roof tiles, concrete	6.10	Layout first floor	70.23
Windows, glass doors	0.45	Layout second floor	65.95
Gypsum	5.60	**Layout total**	**136.18**
Gypsum fibreboard	1.40		
Hollow bricks	64.00		

Wood	6.50		
Filler	0.96		
Mineral wool	0.40		
Mortar	8.60		
PE foil	0.02		
Expandable polystyrene	0.19		
Cladding/finish	0.40		
Fasteners steel	0.09		
Grid support for bricks	2.00		
Concrete for cellar	90.00		
Total without cellar	**117.00**		
Total with cellar	**207.00**		
Energy (kWh/unit)	**41 100.00**		

Life cycle impact assessment for single-family houses

Generally, the waste utilization (materially or thermal) is the last life phase of each product. The higher the amount of renewable building materials, the more fossil fuels can be substituted by energy generation from the waste wood at the end of life cycle of a family house. Unfortunately, LCA studies are often conducted without considering the renewable waste as a potential fuel, however, the energy aspect of renewable waste can be of great importance when conducting a proper impact assessment. In the following cases, the impact assessment is conducted with and without considering the waste wood as fuel.

Case A: No thermal utilization of waste wood

In this case the potential of energy to be generated by thermal utilization of waste wood is neglected. The potential of the impact categories on global warming, acidification, eutrophication and photochemical ozone creation is calculated on the base of energy consumed for production of building materials and construction of the single-family houses concerned. This calculation is too high in comparison with Case B and does not correspond to the real environmental impact. The results obtained can be summarized as follows (see also Table 5):

• The house with the lowest share of wood-based building materials (brick house) shows the most unfavourable impact assessment in comparison with the other two houses.

• Despite the highest amount of wood and wood-based materials, the blockhouse seems to be environmentally less favourable than the timber-frame house.

Case B: Thermal utilization of waste wood

At the end of life cycle, the CO_2-neutral waste wood substitutes the fossil fuels as biomass for energy generation. The analysis of the environmental impact is based on the net energy consumption which is the difference between the energy input (see Table 5/Total) and the energy generated by thermal utilization of renewable waste.

The calculation of the potential energy gaining is based on the calorific value (16 MJ/kg structural timber) and an efficiency of 85 percent. The differentiation between the life cycle phases production and construction is neither feasible nor necessary. The results obtained are shown in Table 6 and lead to the following conclusions:

• The real environmental impacts of the three house types are lower than figures in Table 5.

• The blockhouse is environmentally the most favourable family house followed by the timber-frame house and the brick house.

The results of the environmental impact assessment are also found in Figures 5, 6, 7 and 8. Case A and Case B are also illustrated as "total energy consumption" and "net energy consumption", respectively. The latter one shows the real potentials of the impact categories mentioned above.

Table 5: Case A - Life cycle impact assessment without considering the wood-based waste

House type	Impact potential		Production	Construction	Total
Timber-frame house	GWP100	kg CO_2 eq.*)	70 100.00	24 752.00	94 852.00
	AP	kg SO_2 eq.	156.37	55.21	211.58
	EP	kg phosphate eq.	13.32	4.70	18.02
	POCP	kg ethene eq.	4.03	1.42	5.46
Blockhouse	GWP100	kg CO_2 eq.	71 546.00	24 752.00	96 298.00
	AP	kg SO_2 eq.	159.59	55.21	214.81
	EP	kg phosphate eq.	13.59	4.70	18.30
	POCP	kg ethene eq.	4.12	1.42	5.54
Brick house	GWP100	kg CO_2 eq.	85 277.00	29 702.00	114 980.00
	AP	kg SO_2 eq.	190.22	66.26	256.48
	EP	kg phosphate eq.	16.20	5.64	21.844
	POCP	kg ethene eq.	4.91	1.71	6.616

*) eq. = equivalent

Table **6: Case B - Life cycle impact assessment by considering the wood-based waste**

House type	Impact potential		Total
Timber-frame house	GWP100	kg CO_2 eq.*)	79 248.00
	AP	kg SO_2 eq.	176.78
	EP	kg phosphate eq.	15.05
	POCP	kg ethene eq.	4.56
Blockhouse	GWP100	kg CO_2 eq.	52 957.00
	AP	kg SO_2 eq.	118.13
	EP	kg phosphate eq.	10.06
	POCP	kg ethene eq.	3.05
Brick house	GWP100	kg CO_2 eq.	108 400.00
	AP	kg SO_2 eq.	241.81
	EP	kg phosphate eq.	20.60
	POCP	kg ethene eq.	6.24

*) eq. = equivalent

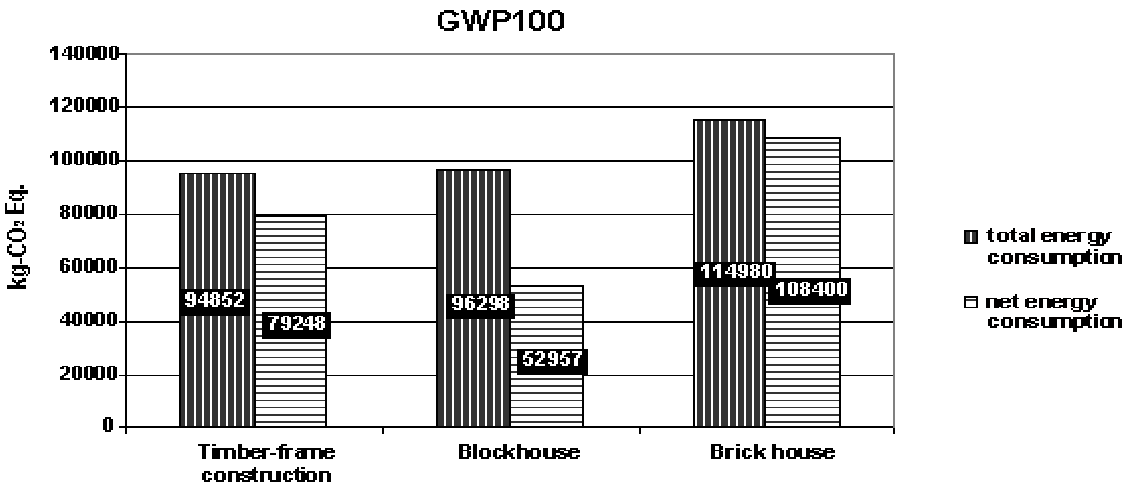
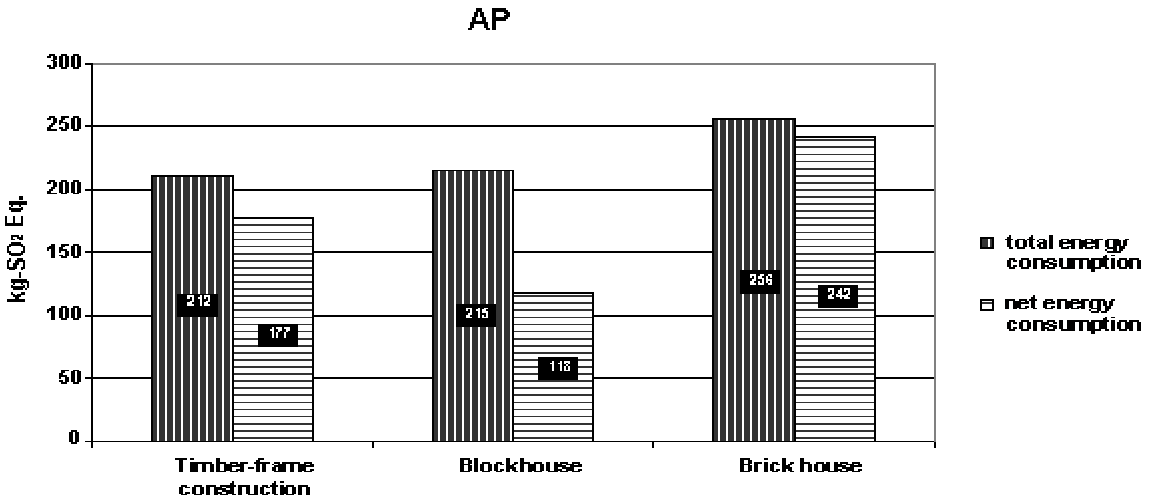


Figure 5: Global warming potential of family houses

Figure 6: Acidification potential of family houses



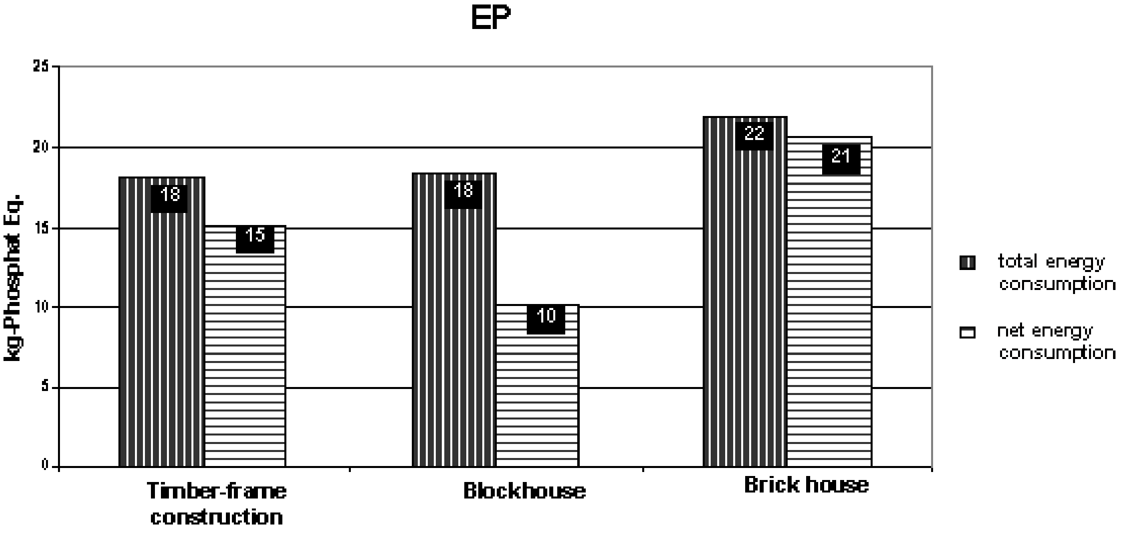


Figure 7: Eutrophication potential of family houses

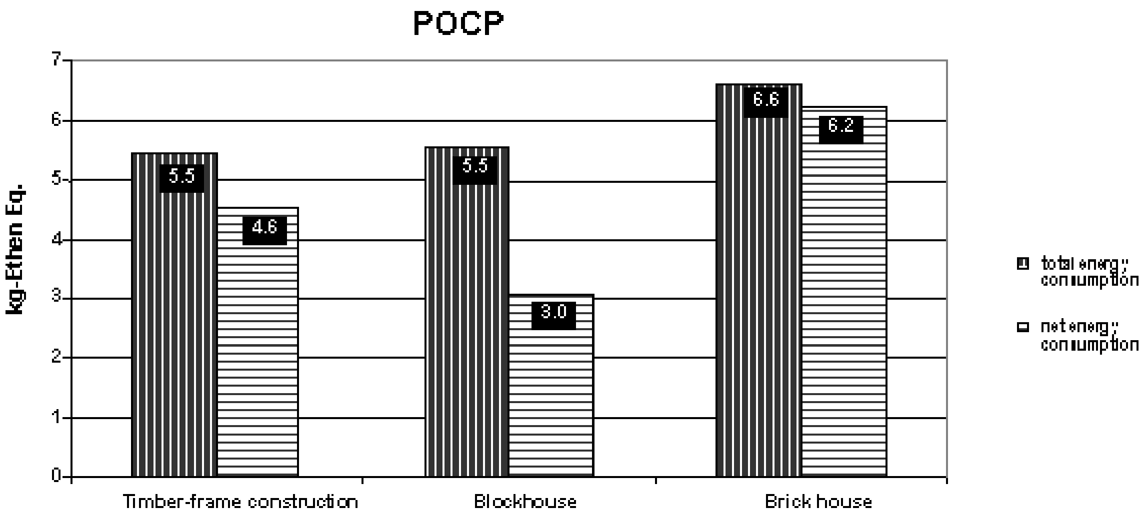


Figure 8: Photochemical ozone creation potential of family houses

LCA of simple large buildings

The ecological advantage of wood as building material can also be demonstrated when used for larger buildings such as stores, factories or similar buildings. The following examples show the lower energy where wood is used as construction material.

Comparison between different three-storey buildings

Definition of buildings

According to the Forintek study (1991), two three-storey buildings with the following characteristics were built:

- area covered by each building: 9 750 m²

- Building 1: made of 1 000 tonnes of wood and 60 tonnes of steel

- Building 2: made of steel only

As shown in Table 7, the energy input for Building 2 is extremely higher than for Building 1. Building 1 contains roughly 1 000 tonnes of timber which can be thermally utilized as waste material at the end of life cycle. Assuming that the average calorific value of timber used in this building amounts to 16 MJ/kg and the efficiency for energy generation is 85 percent, the total energy gaining would be, therefore, around 12 750 GJ, which is more than two times higher than the energy consumed. Building 1, therefore, would contribute to the reduction of the atmospheric CO_2 if by the end of life cycle the renewable waste (1 000 kg of timber) substitutes the fossil fuel.

Table 7: Energy consumption for the construction of three-storey buildings made of different materials (Forintek, 1991)

Building type	Material input	A Total energy input	B Energy gaining	B - A Difference
Building 1				
Wood	1 000 tonnes	5 100 GJ	12 750 GJ	7 290 GJ
Steel	60 tonnes	360 GJ	-	
Building 2				

Steel	2 800 tonnes	17 000 GJ	-	-

LCA results

Case A and Case B which follow demonstrate the two different approaches used for the impact assessment. Case A considers waste wood a useless material to be disposed of or burnt. Consequently, the determination of impact potentials is in favour of Building 2 because the total energy input is the basis of calculations. Case B considers waste wood as a potential energy source which can substitute fossil energy.

Case A: Total energy consumption

The total energy input for Building 1 and Building 2 are 5 460 GJ and 17 000 GJ, respectively. Although this approach does not consider waste wood as energy source and is, consequently, in favour of Building 2, the figures in Table 8 indicate the dominance of wood as an environmentally sound building material. The results obtained show that compared to Building 1 the environmental burdens caused by Building 2 are more than three times higher. The comparison between the two buildings is also shown in Figure 9.

Table 8: Case A - Life cycle impact assessment of two three-storey buildings

		Building 1 (wood and steel)	Building 2 (steel)
GWP100	kg CO_2-eq.	1 096 000	3 410 000
AP	kg SO_2-eq.	2 445	7 613
EP	kg phosphate-eq.	208	648
POCP	kg ethene-eq.	63	196

Case B: Net energy consumption

The waste wood of Building 1 is a CO_2-neutral energy source and provides an additional 7 290 GJ of energy (Table 7) which can replace fossil energy of the same amount. The substitution of fossil fuel would result in the reduction of the corresponding amount of emissions in the atmosphere. Therefore, figures for impact potentials given in Table 9 have negative values and show the importance of timber as environmentally sound building material. The energy input for Building 2, however, remains at the high level of 17 000 GJ.

The advantages of Building 1 and the disadvantages of Building 2 are also shown as histograms in Figures 10 and 11.

Table 9: Life cycle impact assessment of three-storey buildings made of different materials

		Building 1 (wood and steel)	Building 2 (steel)
GWP100	kg CO_2-eq.	- 1 463 000	3 410 000
AP	kg SO_2-eq.	- 3 264	7 613
EP	kg phosphate-eq.	- 278	648
POCP	kg ethene-eq.	- 84	196

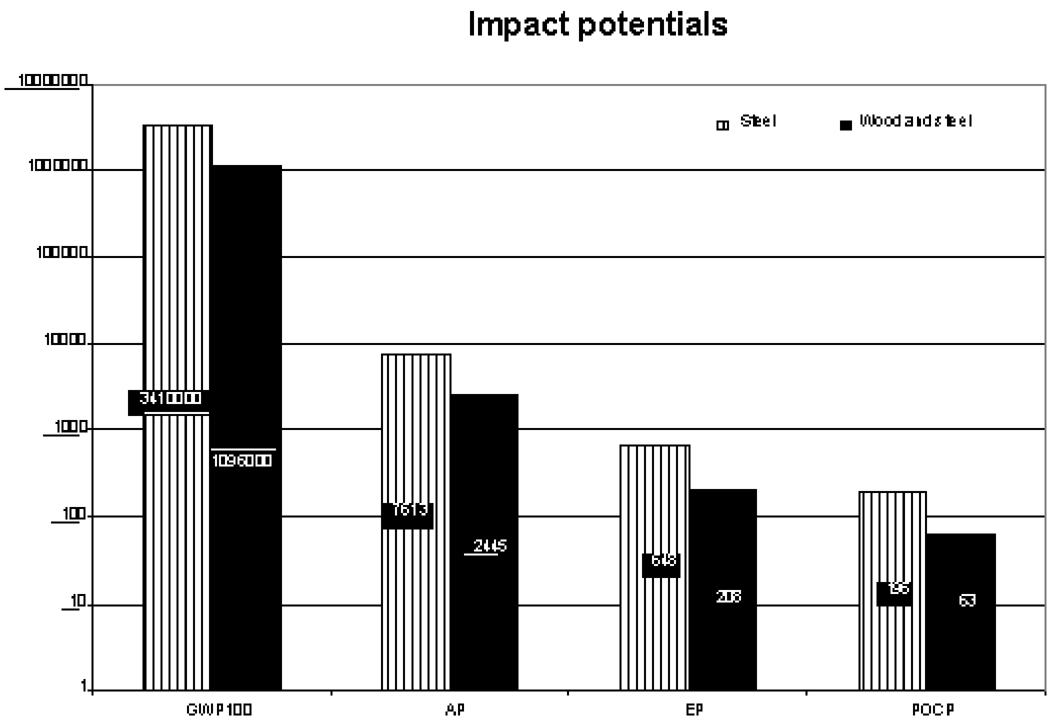
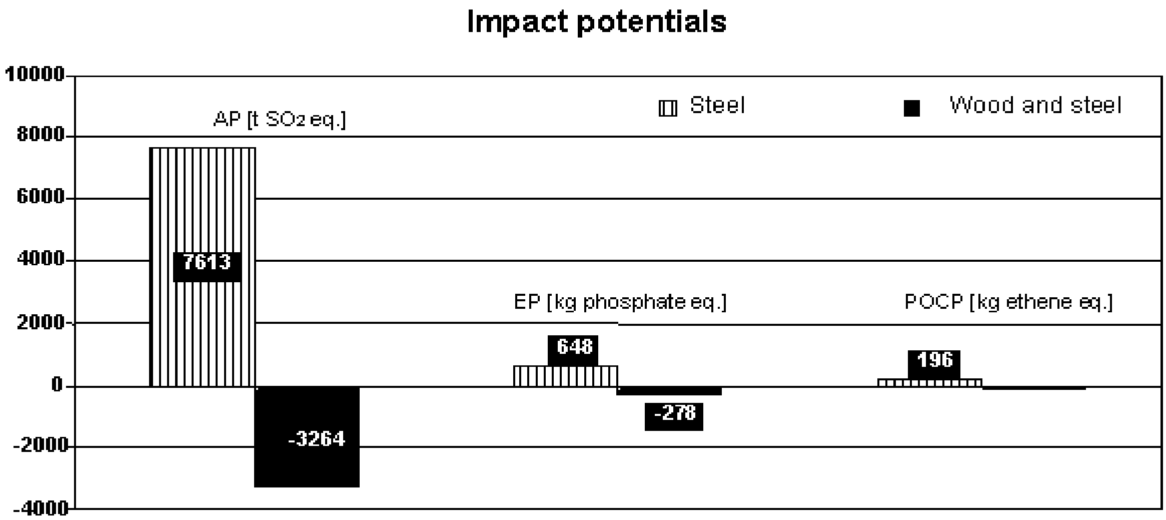


Figure 9: Case A - Logarithmic illustration of an environmental impact assessment of two three-storey buildings

Figure 10: Case B - Environmental impact potential of two three-storey buildings



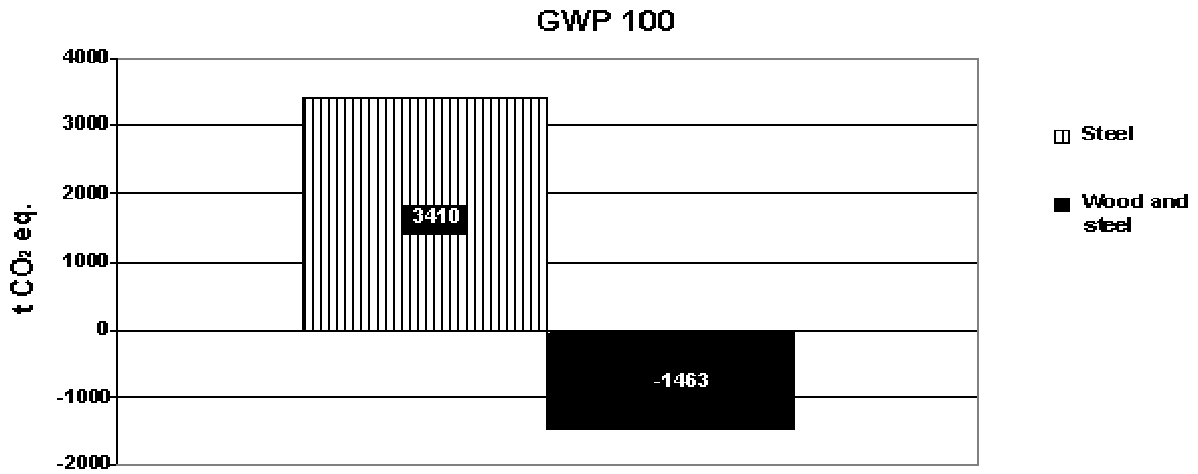


Figure 11: Case B - Environmental impact potential of two three-storey buildings

Comparison between sheds from wood, steel and concrete

Definition of buildings

Baier (1982, quoted in Burschel *et al.*, 1993) investigated the energy consumption for the production, operation and demolition of sheds based on wood, steel and concrete. The three buildings had a covered area of 1 000 m², a functional unit of 6 000 m³ and an average height of 6 m.

As demonstrated in Table 10, the use of wood as the main building material achieved the lowest energy consumption (5 328 GJ), whereas the energy input increased to 6 577 GJ for steel and to 8 003 GJ for concrete as building material. Figure 12 illustrates the energy input for production, transport, operation and demolition in GJ. The operation phase shows the highest energy consumption followed by the production. In the case of concrete as building material, the energy needed for both transportation and demolition is considerably higher than for wood and steel.

The volume of sawnwood in the prefabricated shed is unfortunately unknown, but it can be estimated at around 250-300 tonnes. After the operation time of 20 years and demolition of the wood shed, at least 250 tonnes of waste wood can be utilized for the generation of 3 340 GJ of energy. Therefore, the net energy consumption for the wood shed is only 1 928 GJ.

Table 10: Energy input for production, operation and demolition of sheds based on different materials (Baier, 1982, quoted from Burschel *et al.*, 1993)

Life cycle phases	Energy input (MJ)		
	Wood	Steel	Concrete
Production	1 188 000	2 268 000	2 973 600
Transport	216 000	216 000	435 600
Operation (20 years)	3 600 000	3 870 000	4 100 000
Demolition	324 000	223 000	493 000
Total	**5 328 000**	**6 577 200**	**8 002 800**
Energy from waste	3 400 000	0	0

Net energy consumption	**1 928 000**	**6 577 200**	**8 002 800**

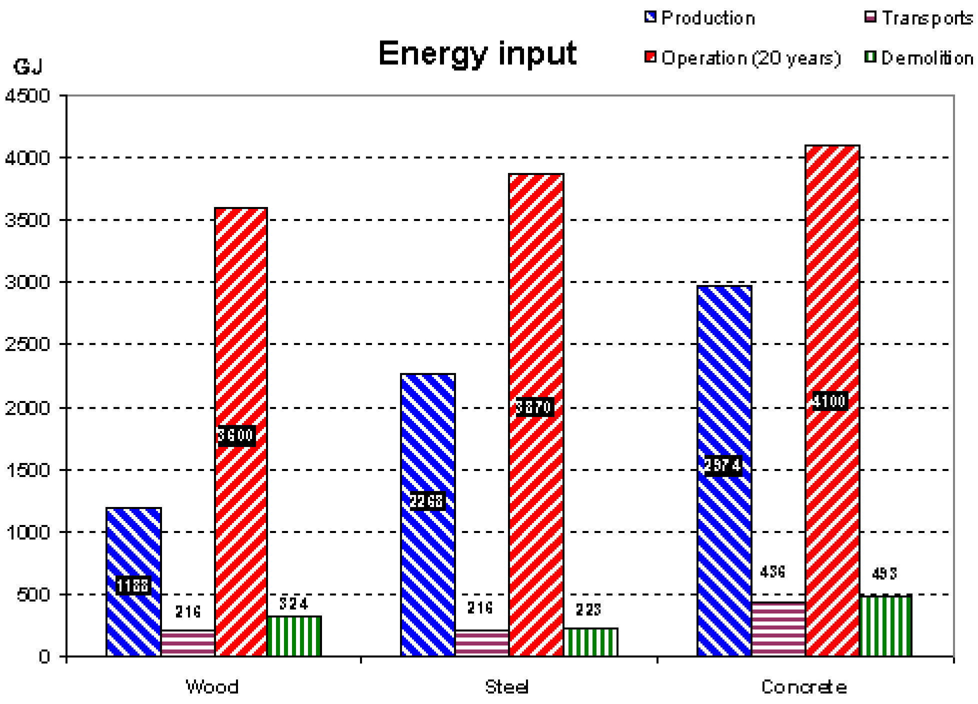


Figure 12: Energy input in different phases of life cycle of sheds

LCA results

The results obtained are shown in Figures 13, 14, 15 and 16. The four columns represent production, transport, operation and demolition. The absolute values of impact potentials are found in the columns concerned. For GWP 100 the values are in tonnes CO_2-eq., while for the other three impact categories the potentials are in kg SO_2-eq (AP), kg phosphate-eq. (EP) and kg ethene-eq. (POCP). The impact assessment of the sheds is conducted for two cases (Case A and Case B).

Case A: Total energy consumption

In this case, the energy input amounts to 5 328 GJ, 6 577 GJ and 8 003 GJ for the sheds from wood, steel and concrete, respectively. The thermal utilization of waste wood is not taken into consideration. The results obtained leads to the following conclusion:

1. Compared with other sheds, the wood shed is the most favourable building because of its low emissions and the resulting impact potentials.

2. Steel and concrete sheds are placed second and third/last.

3. For the three buildings the operation phase of 20 years requires most of the energy consumed and the differences between them are relatively small, e.g. GWP of the wood shed is 7 percent smaller than that of the steel shed and 12 percent smaller than GWP of the concrete shed.

4. Major differences are found in the production phase of the sheds concerned.

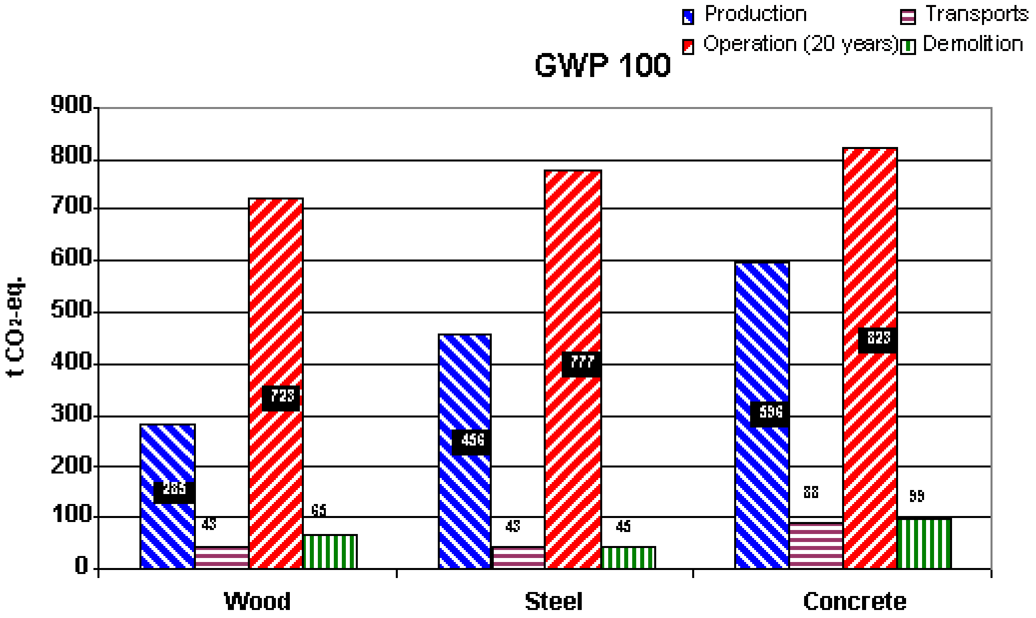


Figure 13: Case A - Global warming potential of sheds based on different building materials

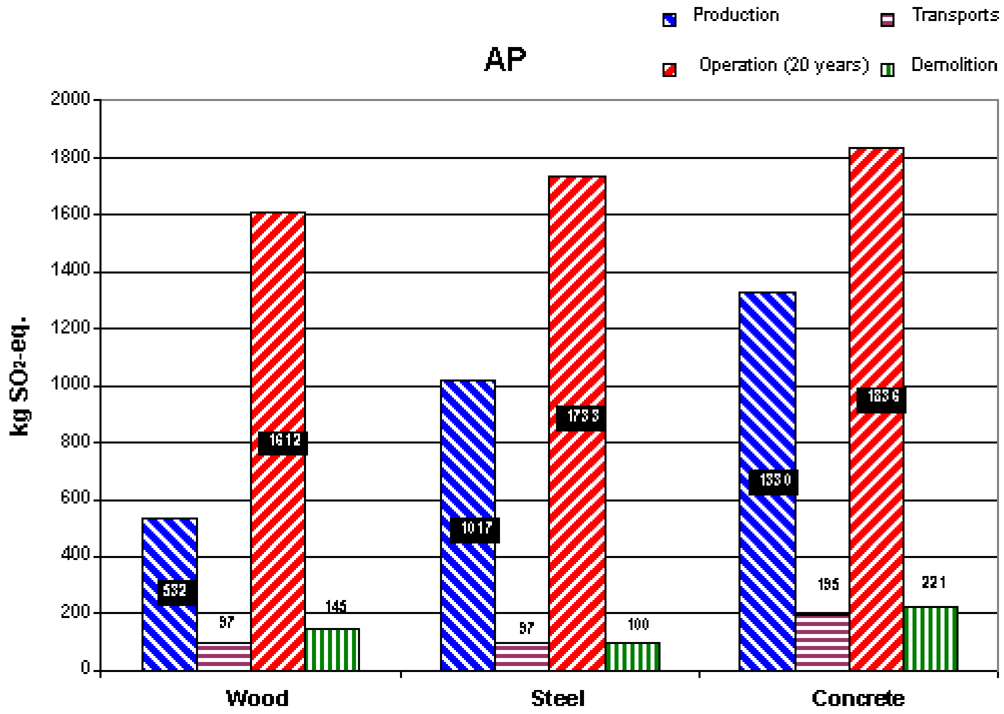
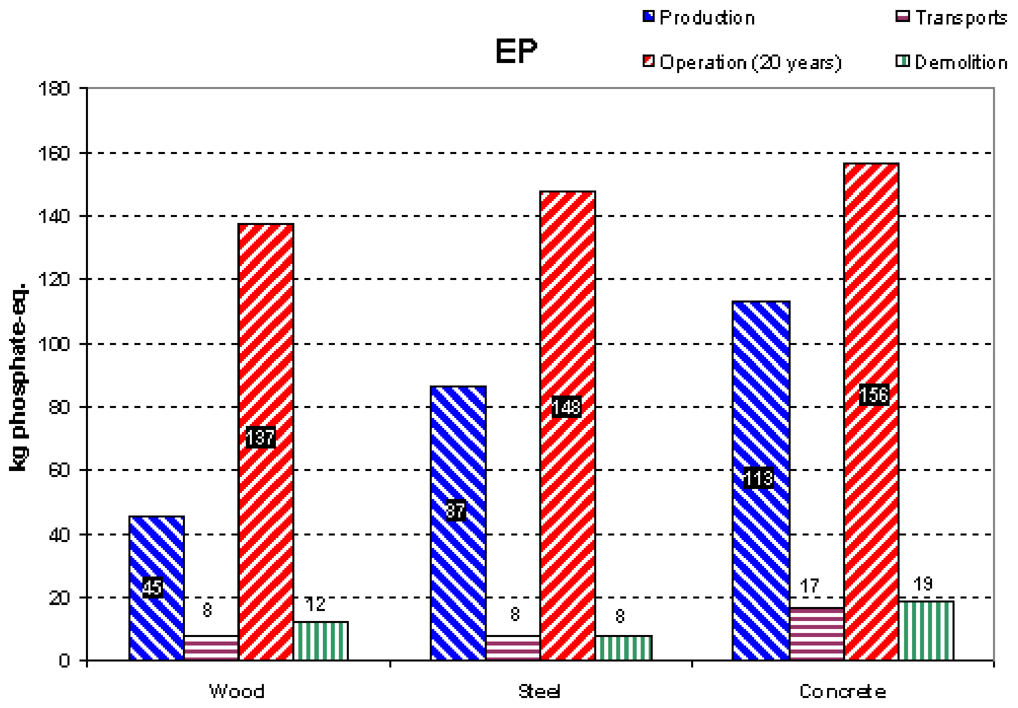


Figure 14: Case A - Acidification potential of sheds based on different building materials

Figure 15: Case A - Eutrophication potential of sheds based on different building



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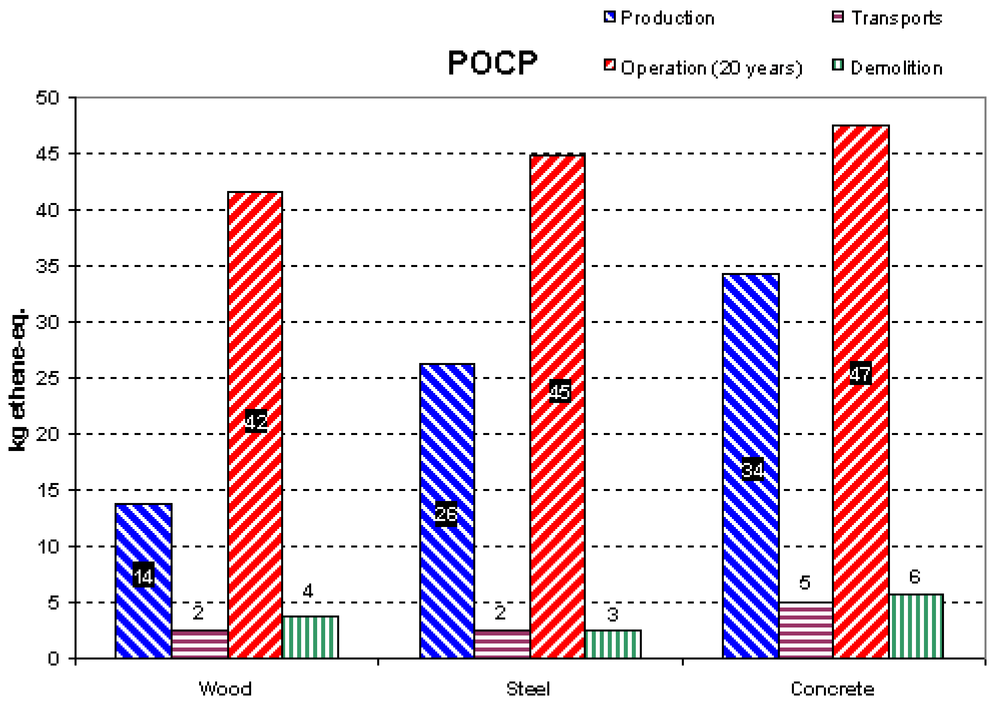


Figure 16: Case A - Photochemical ozone creation potential of sheds based on different building materials

Case B: Net energy consumption

After the operation phase of 20 years, the waste wood is utilized as fuel and at least 3 400 GJ energy are produced. Thus, for the wood shed, the energy consumption and the relating environmental impact potentials are reduced. For the other shed types, however, there is no reduction of energy input and the corresponding environmental impact potentials (compare with Table 10).

The comparison between sheds made of different building materials (wood, steel and concrete) was carried out on the basis of the sum of the net energy consumption for production, transport, operation and demolition. As shown in Figures 17 and 18, the results obtained for the environmental impacts potential are much more in favour of wood as building material.

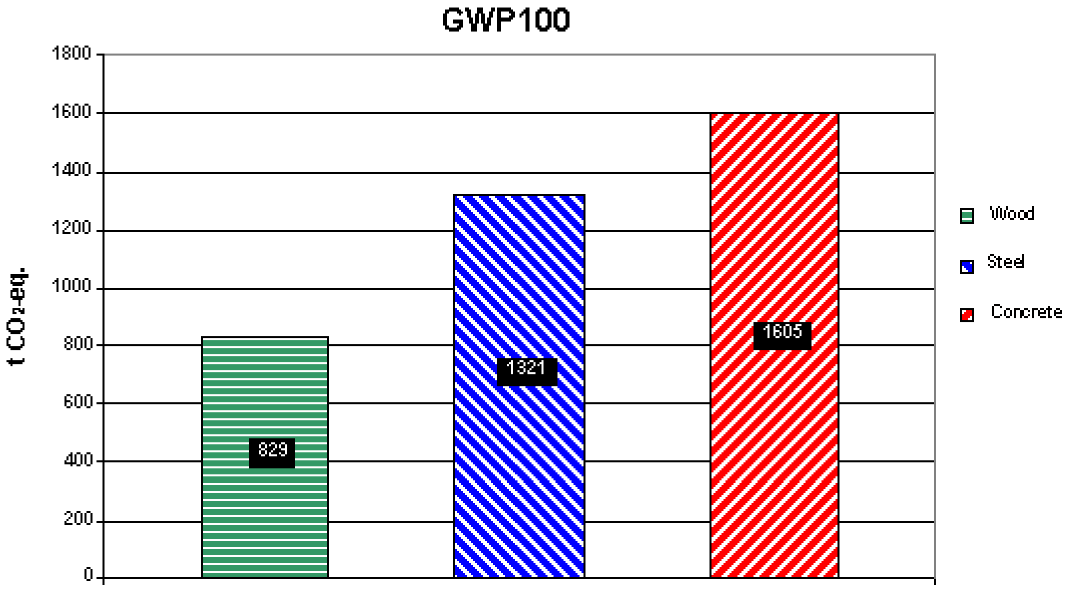


Figure 17: Case B - Global warming potential of sheds based on different building materials

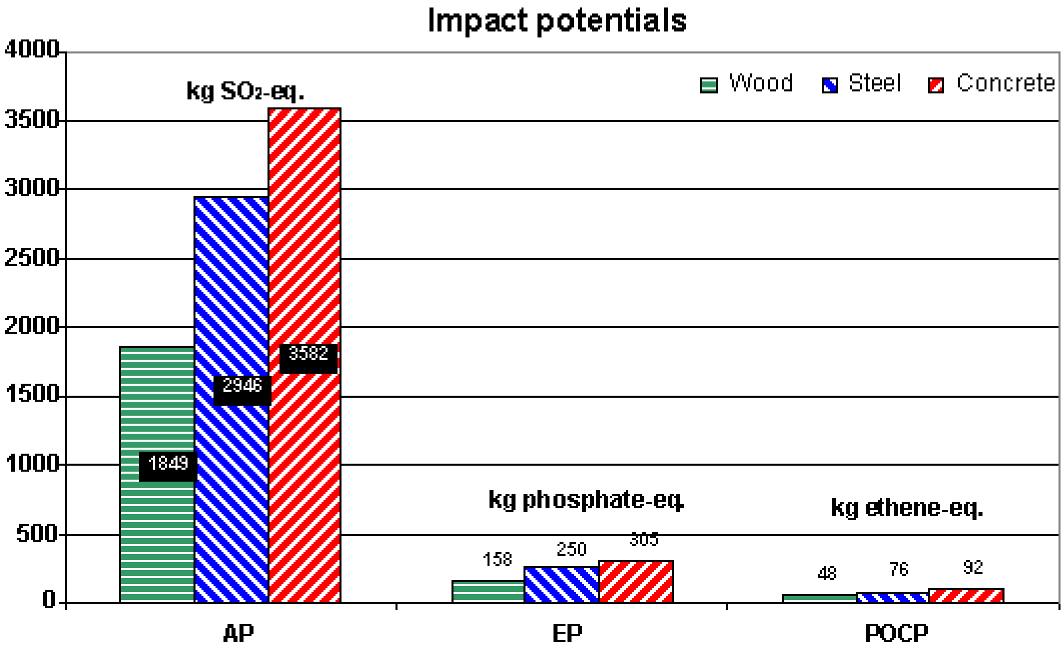


Figure 18: Case B - Environmental impact potential of sheds based on different building materials

LCA of window frames

The ecological comparison of window frames is reported in Richter, Künninger and Brunner (1996) where a comprehensive study was conducted on LCA for window frames made of different materials. Below, the results of LCA of window frames from wood, PVC and aluminium are compared.

Definition of products

The products investigated are aluminium, PVC and wooden windows, and it is assumed that the glazing is the same for the three frame types and, therefore, the glass is not included in the analysis of impact assessment. The functional unit is a two-wing window of 1 650x1 300 mm (see also Figure 19).

The system boundaries are between the modules (life cycle phases) raw material gathering/raw material production at the beginning of product life and waste disposal at the end of life cycle. The single modules taken into account are "raw material gathering/production", "raw material preparation", "window installation - using period - dismantling" and "waste disposal". Waste disposal means recycling for PVC and aluminium frames. Waste wood is normally utilized as fuel/energy carrier while contaminated wood is landfilled.

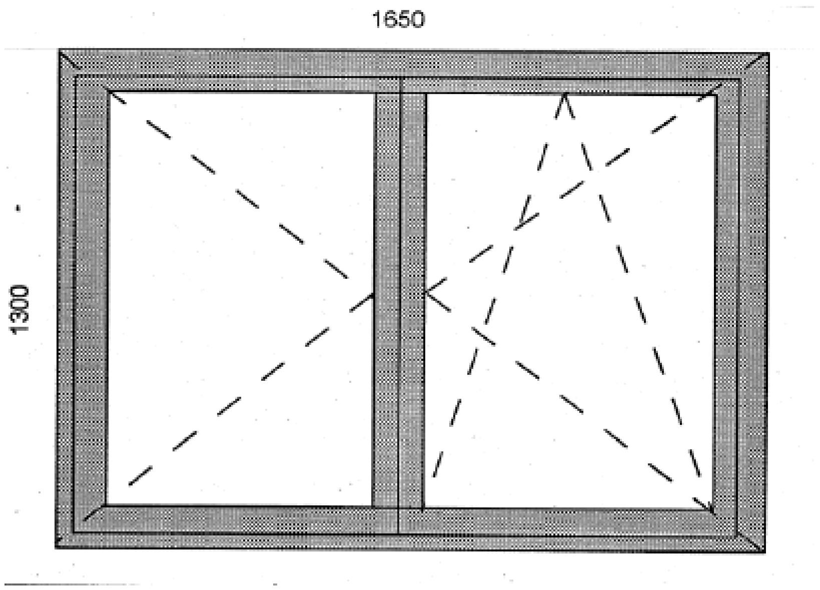


Figure 19: Two-wing window frame as functional unit

Comparison between aluminium, PVC and wooden windows

Table 11 shows the net weight and the k-value of the three frame types. The wood frame results with the lowest weight and together with PVC results also with the lowest k-value and therefore wood and PVC frames are favoured compared to aluminium frames.

Table 11: Net weight and k-value of window frames

Frame type	Net weight	k-value
Aluminium	31.65 kg	1.9 W/m²K
PVC	43.73 kg	1.5 W/m²K
Wood	26.43 kg	1.5 W/m²K

Input of energy and material

According to Richter, Künninger and Brunner (1996), the net input of the aluminium, PVC and wood per window unit amounts to 28.5 kg, 26 kg and 20.7 kg, respectively. Details concerning the input of various materials are shown in Tables 12, 13 and 14. By considering all modules (life cycle phases) within the system boundaries mentioned before, the total energy consumption amounts to 26.6 GJ/unit for aluminium window, 20.8 GJ for PVC window and 19.2 GJ for wooden window (see Figure 20).

Table 12: Materials for aluminium window

	Transportation	Input (kg/unit)		
Materials	(km)	Total	Window frame	Residues

Aluminium profile	150	28.69	27.54	1.15
Aluminium sheet	180	0.67	0.65	0.03
Polyamide/glass fibre	600	4.88	4.88	-
EPDM	600	2.84	2.84	-
Aluminium cast	600	0.33	0.33	-
Steel, stainless	600	0.38	0.38	-
Steel, galvanised	600	0.22	0.22	-
Brass	600	0.04	0.04	-
Zinc die-casting	600	2.18	2.18	-
PE (HD)/polyethylene	100	0.14	0.14	-
Isopropanol	100	0.02	-	0.02
Epoxid	100	0.07	0.07	-
PES	100	0.38	0.38	-

Table 13: Materials for PVC window

	Transportation	Input (kg/unit)		
Materials	(km)	Total	Mass frame	Residues
PVC profiles	600	27.55	25.57	1.980
Steel, fire galvanised	500	14.58	14.53	0.055
Aluminium profile	100	0.43	0.42	0.004
EPDM	200	0.78	0.75	0.022
PVC-NBR	600	0.51	0.45	0.052
Steel, stainless	700	1.64	1.58	0.056
Zinc die-casting	700	0.14	0.14	-
Steel screws	700	0.05	0.05	-
Polyamide	700	0.01	0.01	-
Polypropylene	100	0.06	0.06	-
EPS exp.	100	0.05	0.05	-
Steel screws	100	0.08	0.08	-
Gum glue	100	0.005	0.005	-
PVC bonding agent	100	0.01	0.01	-
POM	100	0.01	0.01	-
Polyester powder	100	0.01	0.01	-

Table 14: Materials for wooden window

	Transportation	Input (kg/unit)		
Materials	(km)	Total	Mass frame	Residues
Spruce squared timber	350	36.84	19.72	17.14
Aluminium profile	100	1.28	1.25	0.03
EPDM	200	0.95	0.90	0.05
Silicon	100	0.36	0.32	0.04
Steel sheet	700	1.64	1.56	0.08
Zinc die-casting	700	0.12	0.12	-
Steel screws	700	0.05	0.05	-
Polyamide	100	0.01	0.01	-
PVAc	700	0.13	0.13	-
Spruce strips	100	0.88	0.80	0.08

Beech wood	100	0.11	0.11	-
Epoxid	100	0.01	0.009	0.001
PE (HD)	100	0.005	0.005	-
Polyamide	100	0.005	0.005	-
Acylate spatula	100	0.005	0.005	-
Filling material, filler	1000	0.44	0.44	-
Acetyl coating, covering lacquer	1000	1.49	0.99	-
Polyester powder	100	0.04	0.04	-

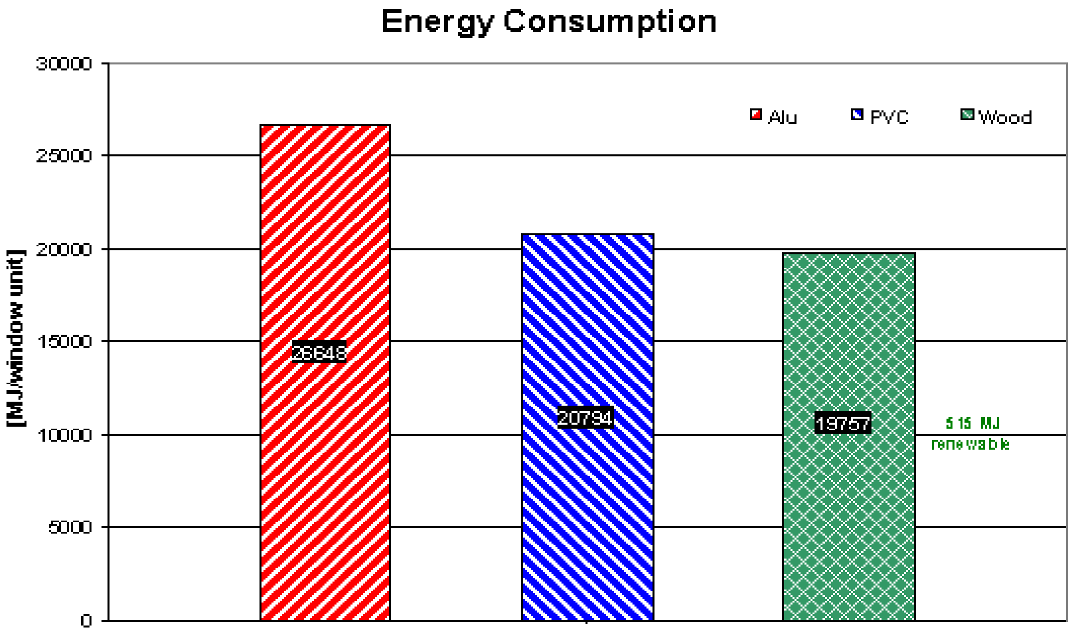


Figure 20: Total energy consumption in MJ/unit window

Life cycle impact assessment

The results of the impact assessment for each impact category are illustrated in Figures 21, 22, 23 and 24 and demonstrate that:

- for all impact categories concerned, the environmental burdens of the wooden window are the lowest;

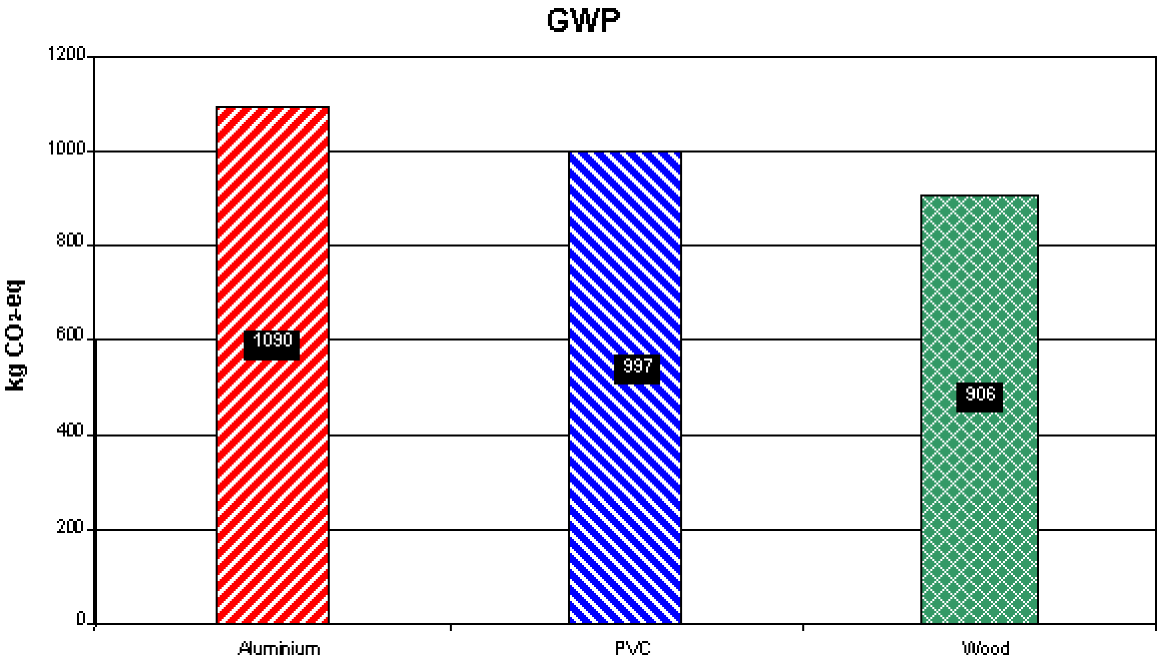
- in the case of the wooden window, the waste wood can replace fossil fuel so that the net environmental impact might be even smaller than shown in Figures 21, 22, 23 and 24;

- AP of the wooden window is only 40-47 percent of that of aluminium and PVC windows; and

- concerning the EP and POCP, the results for the wooden window are around two-thirds of that for other windows.

Figure 25 gives a global view of the results. Due to the big differences in absolute values between the categories, the histograms are illustrated in the logarithmic form and, therefore, more attention should be paid to the figures in the histograms.

Figure 21: Global warming potential of windows made of different raw materials



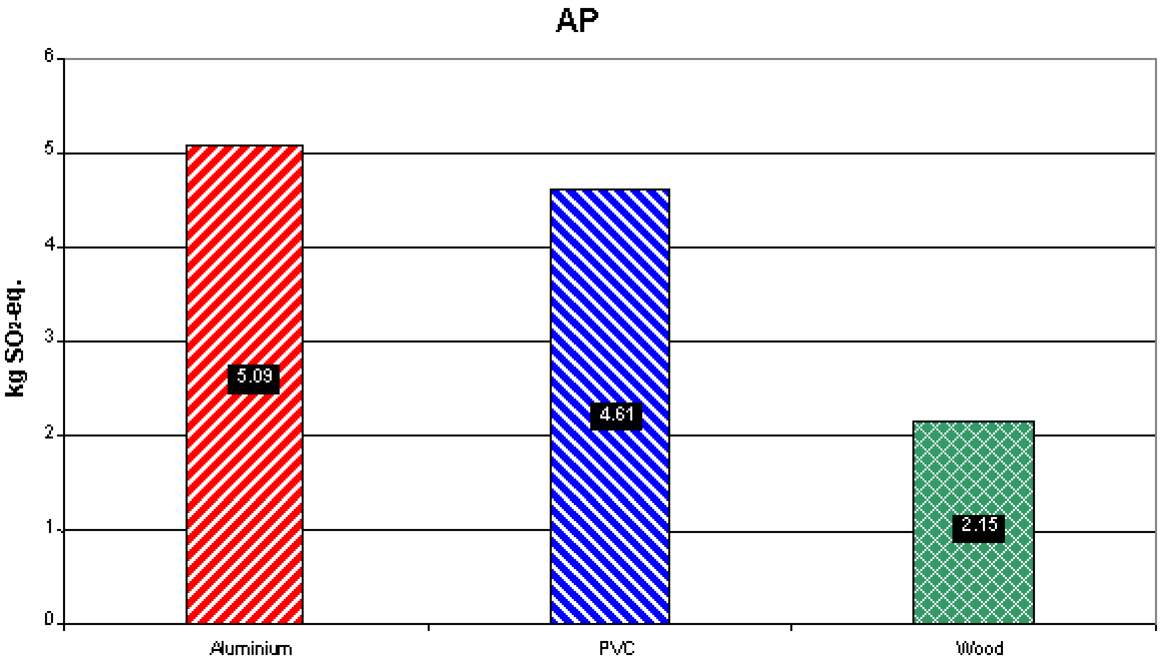
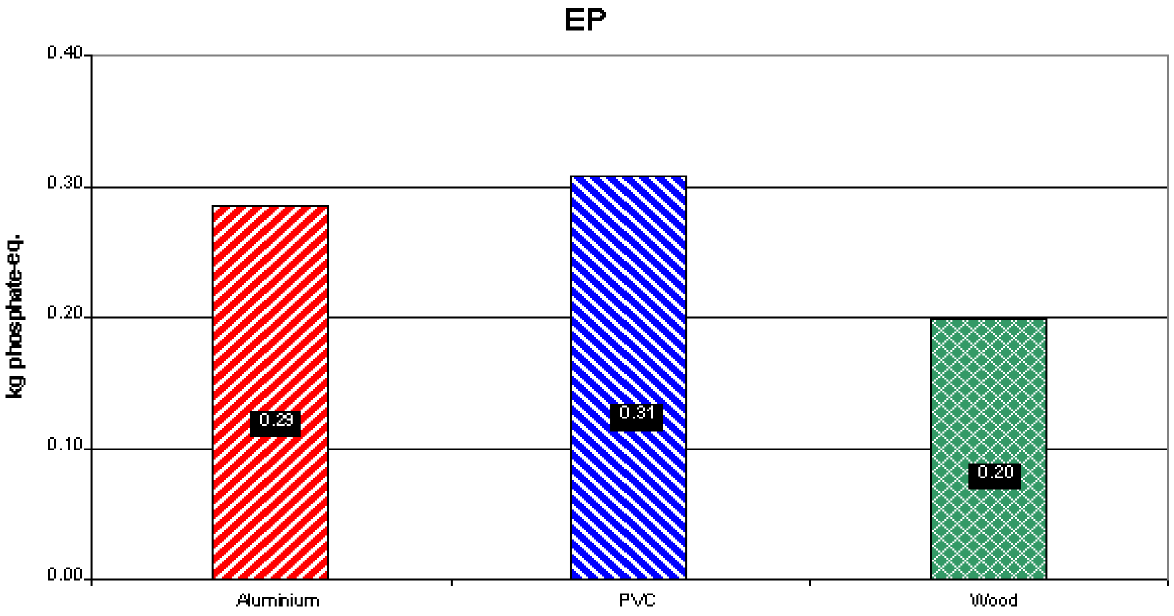


Figure 22: Acidification potential of windows made of different raw materials

Figure 23: Eutrophication potential of windows made of different raw materials



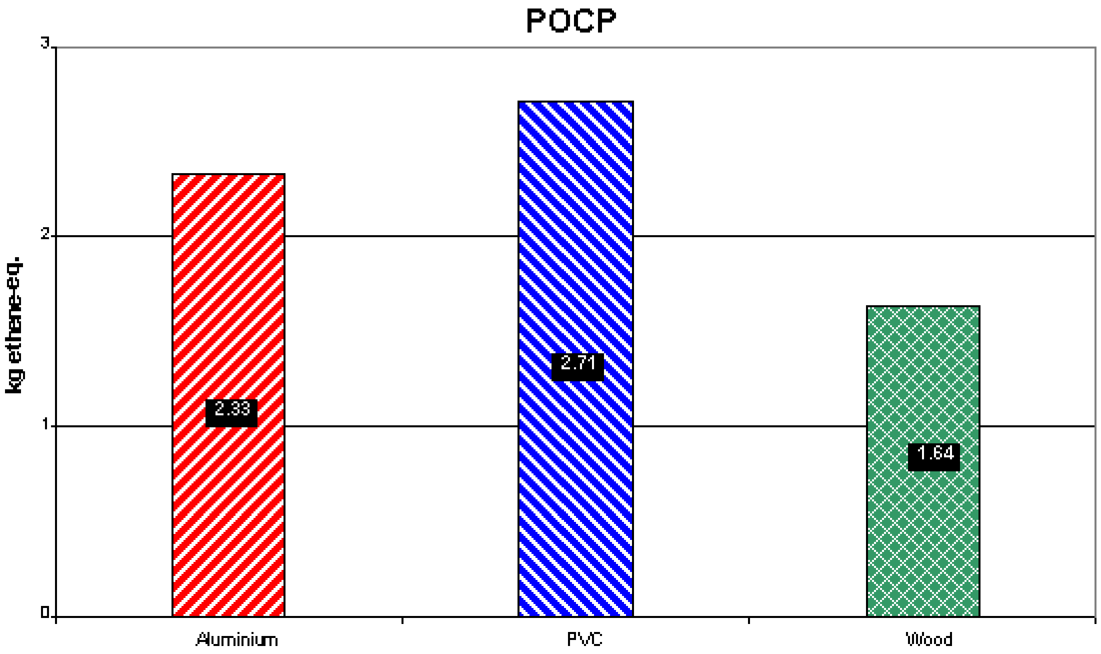
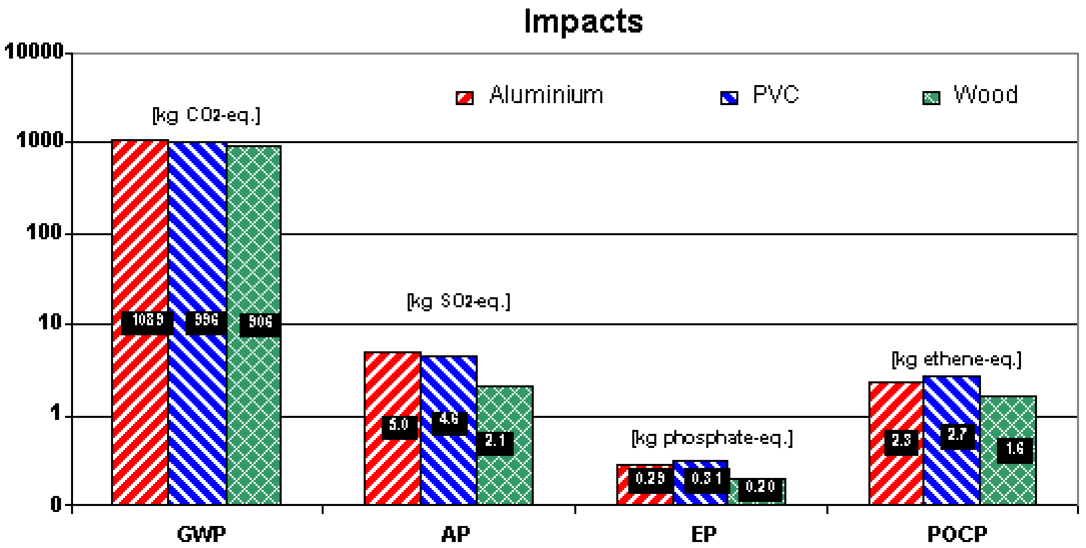


Figure 24: Photochemical ozone creation potential of windows made of different raw materials

Figure 25: Logarithmic illustration of impact potentials



As mentioned before, for the conduction of LCA studies, the life cycle is divided into modules or phases. Regarding the material and energy flow, the modules differ from each other and, therefore, the consumption of energy and particularly that of fossil energy varies for different modules. On the other hand, the extent of environmental impacts depends very much on the amount of energy consumed. It should be remarked that transport is necessary for almost all modules, but to simplify the calculation all transports are regarded as a separate module.

In the case of windows, the authors of this study try to highlight the differences in the impact potentials for various modules and these differences result from different energy consumption:

- Concerning GWP, the lifetime impact of windows is significantly high and due to the periodical treatment with paint, lacquer or other chemicals the wooden window results in having the highest impact followed by PVC and aluminium. However, when the entire life cycle is considered, the wooden window is the most favourable product and the PVC and aluminium window are placed second and last, respectively.

- With regard to AP and EP, the effect resulting from the window transport is for aluminium and PVC almost the same and considerably higher than that for the wooden window (Figures 27 and 28). Concerning POCP, the transport effect is again for the wooden window the lowest, followed by aluminium and PVC windows (Figure 29).

- From the viewpoint of frame material, the wooden window shows the lowest AP, EP and POCP and aluminium and PVC are alternately placed second and third (Figures 27, 28 and 29).

- Concerning the environmental impact of lifetime, AP, EP and POCP are for the three window types almost the same but the wooden window shows slightly higher potentials than the other window types.

Figure 26: GWP of different modules

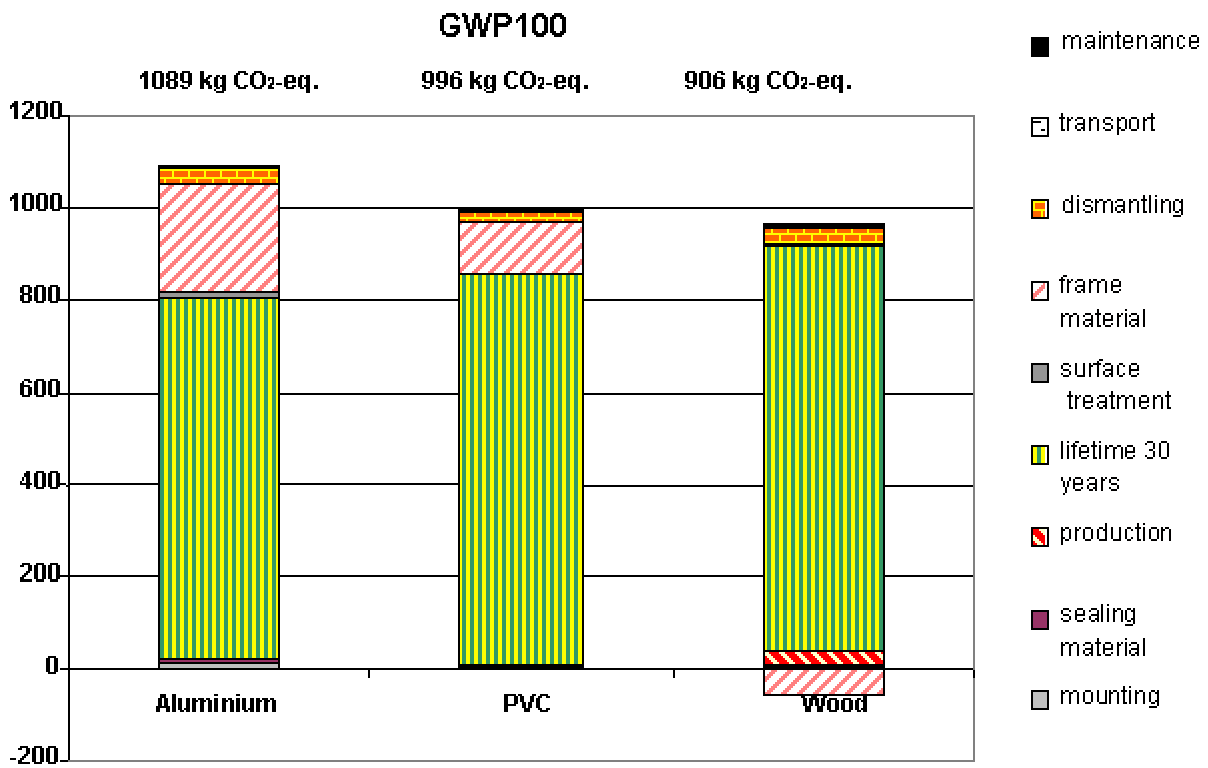


Figure 27: AP of different modules

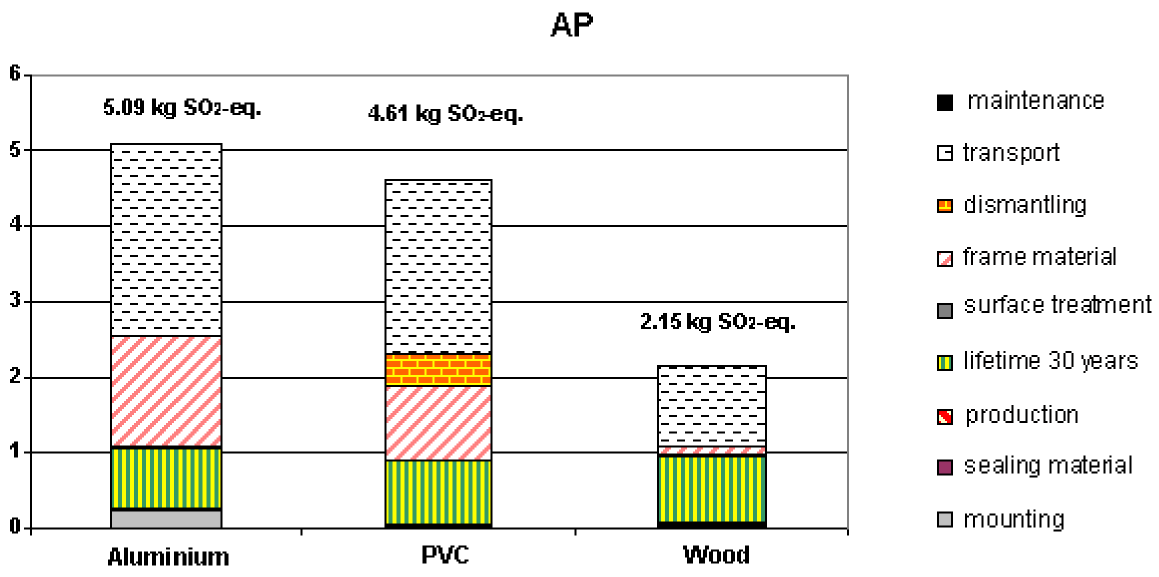


Figure 28: EP of different modules

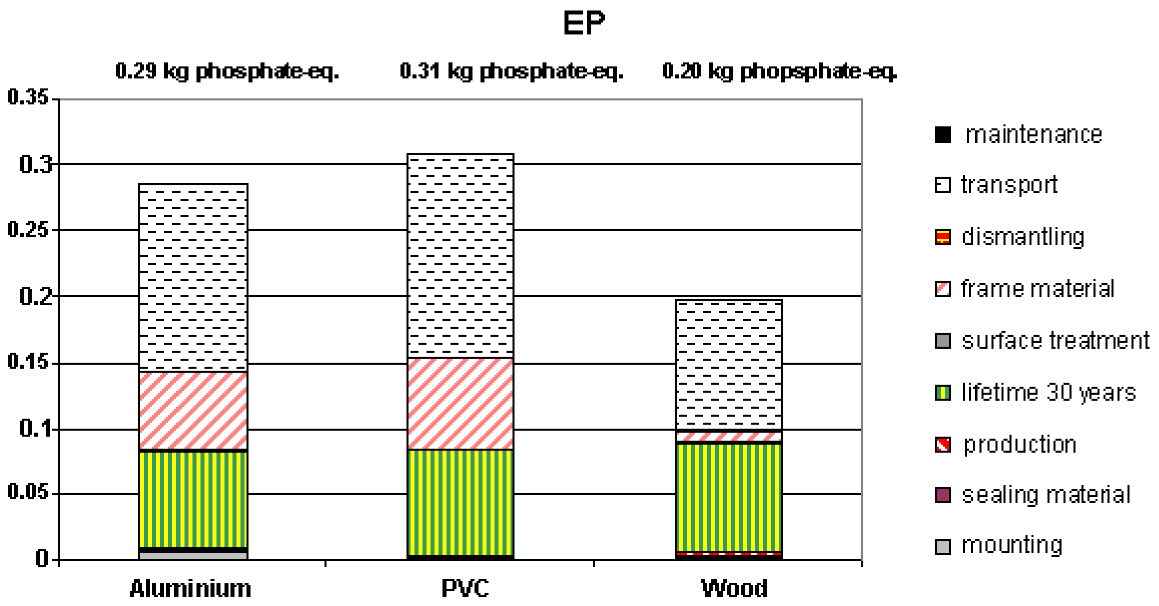
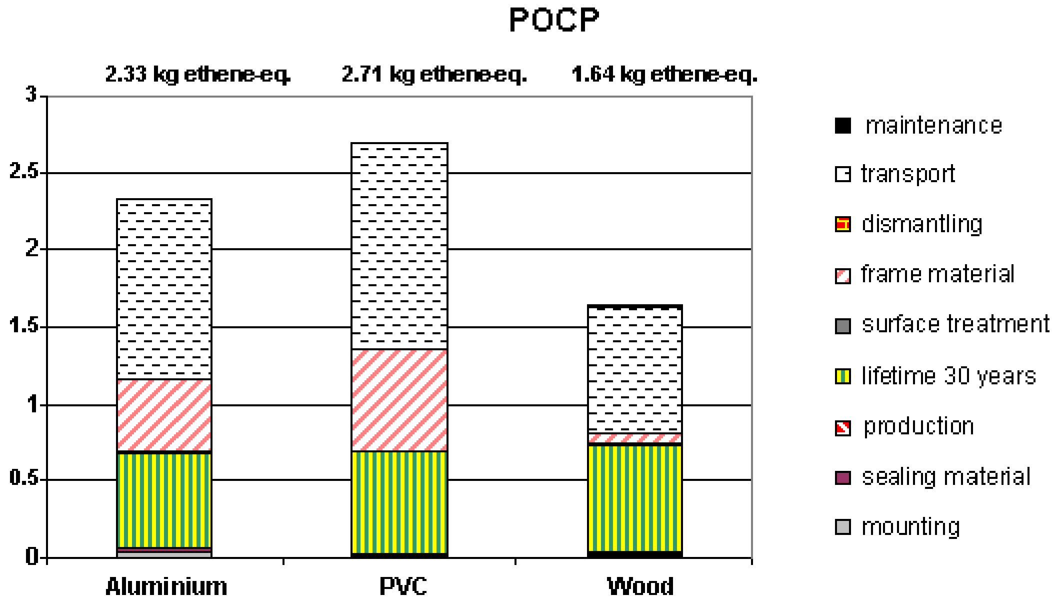


Figure 29: POCP of different modules



LCA of flooring materials

Wood, PVC and linoleum as flooring materials

The study on LCA for flooring materials is part of a postgraduate work carried out by Åsa Jönsson (1995) at the Department of Technical Environmental Planning of the Chalmers University in Göteborg, Sweden. The objective of this study was to compare different flooring materials on the basis of their environmental impacts and to develop the methodology for LCA of building materials.

Definitions

Three types of flooring materials were studied: linoleum, PVC flooring and solid wood flooring (pine). Linoleum components are surface layer (acrylate), linseed oil, resin, powdered wood and cork, powdered limestone, pigment, jute and drying agents. The main ingredients of PVC are chlorine (Cl_2) and ethylene (CH_2-CH_2). The three materials shall be used in dry rooms although PVC flooring is also suitable for damp rooms. Moreover, the scope of the study was confined to private dwellings and therefore non-residential uses were excluded.

The functional unit is 1 m². Due to the different lifetimes, the proper comparison between the different flooring materials concerned is feasible if the results given in Tables 15, 16 and 17 and in Figures 31, 32, 33, 34, 35 and 36 are divided by the number of years. The estimated lifetimes were: linoleum, 25 years; PVC flooring, 20 years; and solid wood flooring, 40 years. The transition from a technical system to a natural system was chosen as system boundaries. Consequently, production, lifetime and the necessary maintenance, transport and waste disposal were included in the analysis.

For the waste disposal, it was assumed that all flooring materials would be incinerated after use, so that the environmental impact of waste disposal was comparable for the three materials. Besides flooring materials, floor adhesive, cleaning agents and other environmentally relevant inputs were also included in the calculation (Åsa Jönsson, 1995).

The inventory results of the study provided a database for the manufacturers of flooring material and the target groups were, therefore, the Swedish producers and not the consumers.

Comparison between different flooring materials

As mentioned above, the results obtained are related to 1 m² and for a proper comparison between the different flooring materials concerned, the environmental loads have to be divided by the lifetimes. However, even by neglecting the lifetime, wood is the most favourable flooring material.

Tables 15, 16 and 17 list the inputs of materials and energy as well as the output in the form of gaseous, liquid and solid emissions and it can be noted that beside wood flooring, linoleum contains a considerable amount of renewable materials (wood, cork, linseed, jute fibres), whereas, the resources for PVC production are non-renewable. At the end of life cycle, waste materials can be utilized for energy generation and by comparing renewable and non-renewable waste material, the benefits of waste wood becomes clear because of the following:

- By burning wood the release of CO_2 has no negative effects because it was removed from the atmosphere by photosynthesis.

- Renewable components of linoleum are, similarly to wood, CO_2-neutral and do not contribute to global warming.

- Non-renewable materials as components of linoleum and PVC cause negative effects due to the additional CO_2 released to the atmosphere.

- Besides the CO_2-neutrality, the renewable waste can substitute an equivalent amount of fossil fuels leading to the reduction of CO_2 in the surrounding atmosphere.

The energy input and energy potential for each flooring products are also found in Tables 15, 16 and 17. Accordingly, pinewood as flooring material consumes the lowest amount of energy (electricity and fossil energy) followed by linoleum and PVC and by using the waste as fuel the net energy consumption for linoleum and PVC reduces to 13 MJ-eq./m² and 29 MJ-eq./m², respectively. In the case of wood as flooring material, the energy potential of waste exceeds the energy consumption and, therefore, as shown in Figure 30, the net energy consumption (-64 MJ/m²) for wood flooring is negative and corresponds to almost 2 litres of light oil or diesel which means that 1 m² of wood flooring reduces the environmental impact of 2 litres of diesel.

For the conduction of the life cycle impact assessment, priority should be given to the emissions which are in direct relationship with the impact categories analysed in this study. These are CO_2, SO_2, NO_X, HC, CH_4, VOC and HCl and show the following impact potentials:

- PVC shows the highest GWP (4.2 kg/m²) which is 2.5 times more than that of linoleum (1.6 kg/m²) and that wood is very small (0.42 kg/m²) and can be more or less neglected (see Figure 31).

- Regarding AP, PVC is again placed first followed by wood and linoleum. The fact that wood shows higher potential than linoleum might be related to the incineration process (Figure 32).

- The ecologically most unfavourable result for wood flooring is the relatively high EP (Figure 33), whereas PVC flooring shows the lowest EP. Concerning POCP, however, wood as flooring material is the best (Figure 34), whereas PVC and linoleum are placed second and last, respectively.

Table 15: Total environmental loads per 1 m² of linoleum (Åsa Jönsson, 1995)

Parameter	Amount per 1 m²		Main source
Resources			
Acrylate	2.5	g	Raw material
Titanium dioxide	102	g	Raw material
Limestone	460	g	Raw material
Resin	204	g	Raw material
Wood	767	g	Raw material
Cork	128	g	Raw material
Jute fibre	280	g	Raw material
Linseed	588	g	Raw material
K_2O	13.5	g	Fertilizer
P_2O_5	16.5	g	Fertilizer
Energy			
Electricity	16.3	MJ	Linoleum production (44%) Titanium dioxide (30%)
Fossil fuel Calorific value	25.00 45.20	MJ MJ	Linoleum production (67%)
Recovered energy	- 28.8	MJ	Incineration
Emission to air			
CO_2	1600	g	Linoleum production (58%)
CO	1.06	g	Transportation (80%)
SO_2	4.3	g	Transportation (40%)
NO_X	12.8	g	Incineration (40%) Transportation (31%)
VOC	5.87	g	Linoleum production (87%)
Solvents	3.12	g	Linoleum production
Terpenes	0.034	g	Powdered wood
Dust	34.50	g	Powdered limestone (96%)
Emission to water			
Oil	0.002	g	Transportation (65%)
Phenol	0.00003	g	Transportation (65%)
COD	0.007	g	Transportation (65%)
tot-N	0.001	g	Transportation (65%)
Waste			
Ash	555	g	Incineration
Sector-specific waste	17.2	g	Jute fibre production
Hazardous waste	238	g	Titanium dioxide production

Table 16: Total environmental loads per 1 m² of PVC flooring (Åsa Jönsson, 1995)

Parameter	Amount per 1 m²		Main source
Resources			
Crude oil	1420	g	Raw material
Rock salt	378	g	Raw material
Limestone	86.6	g	Raw material
Titanium dioxide	43.3	g	Raw material
Glass fibre	57.8	g	Raw material
Sulphuric acid	130	g	Titanium dioxide
Energy			
Electricity	18.2	MJ	Flooring production (53%) PVC production (30%)
Fossil fuel Calorific value	26.5 27.3	MJ MJ	Petrochemical industry (73%)
Recovered energy	- 16	MJ	Incineration
Emission to air			
CO_2	4140	g	Incineration (53%)
CO	0.51	g	Fossil fuels
SO_2	4.87	g	Fossil fuels
NO_X	8.36	g	Fossil fuels
HC	1.94	g	Fossil fuels
Ethylene	0.06	g	PVC production
CH_4	3.08	g	Flooring production
VOC	1.95	g	Flooring production (94%)
Mercury (Hg)	0.00006	g	PVC production
EDC/EC/VCM	0.56	g	PVC production
HCl	23.4	g	Incineration
Dust	6.79	g	Filter production (92%)
Emission to water			
Oil	0.03	g	Transportation (65%)
Phenol	0.0005	g	Transportation (65%)
COD	0.65	g	Transportation (65%)
tot-N	0.02	g	Transportation (65%)
Mercury (Hg)	0.00002	g	PVC production
PVC	0.05	g	PVC production
Sodium formiate	0.08	g	PVC production
EDC/VCM	0.65	g	PVC production
Waste			
Ash	801	g	Incineration
Sector-specific waste	197	g	Flooring production (74%) Rock salt extraction (24%)
Hazardous waste	121	g	Titanium dioxide production

Table 17: Total environmental loads per 1 m² of solid wood flooring (Åsa Jönsson, 1995)

Parameter	Amount per 1 m²		Main source
Resources			
Wood	7.4	g	Raw material
Energy			
Electricity	8.37	MJ	Sawmills
Fossil fuel	5.39	MJ	Transportation (74%)
Calorific value	45.20	MJ	Felling etc. (26%)
Renewable fuels	35.4	MJ MJ	Sawmills
Calorific value	126		
Recovered energy	-113	MJ	Incineration
Emission to air			
CO_2	424	g	Transportation
CO	0.037	g	Sawmills (96%)
SO_2	1.89	g	Sawmills (56%) Transportation (24%)
NO_X	31.6	g	Incineration
HC	0.98	g	Transportation
Terpenes	3.33	g	Wood (100%)
Dust	1.24	g	Transportation (48%) Sawmills (36%)
Emission to water			
Oil	0.002	g	Transportation (74%)
Phenol	0.00003	g	Transportation (74%)
COD	0.006	g	Transportation (74%)
tot-N	0.001	g	Transportation (74%)
Waste			
Ash	198	g	Incineration (75%) Sawmills (25%)

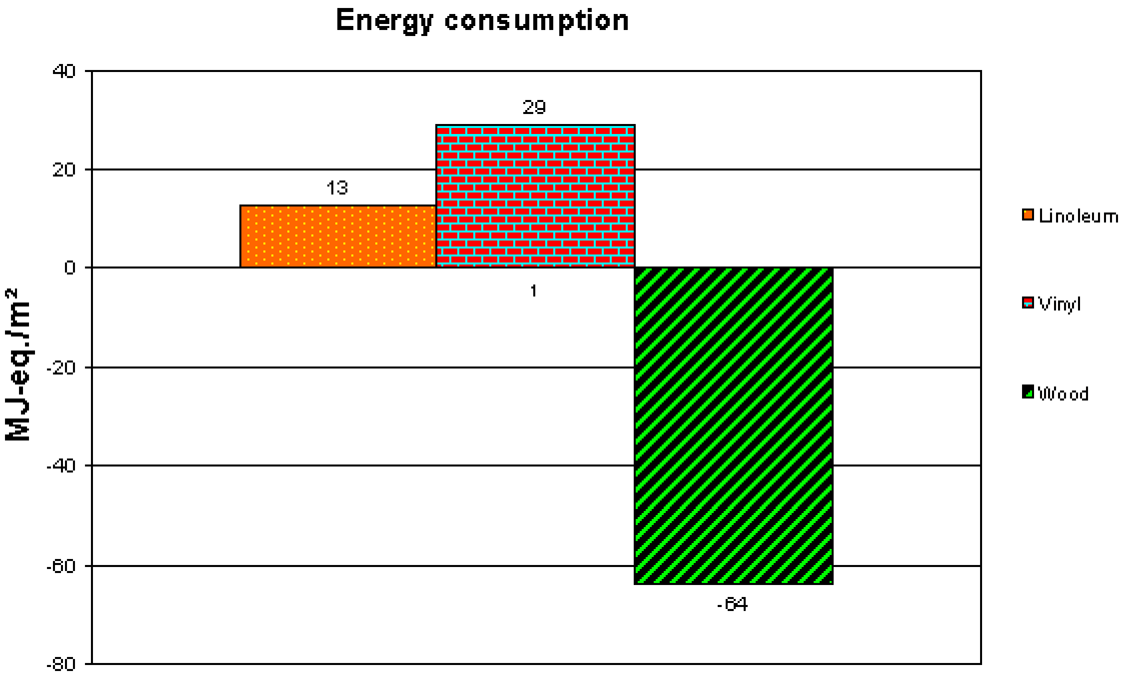


Figure 30: Net energy consumption for 1 m² of flooring materials; in the case of wood net energy gaining

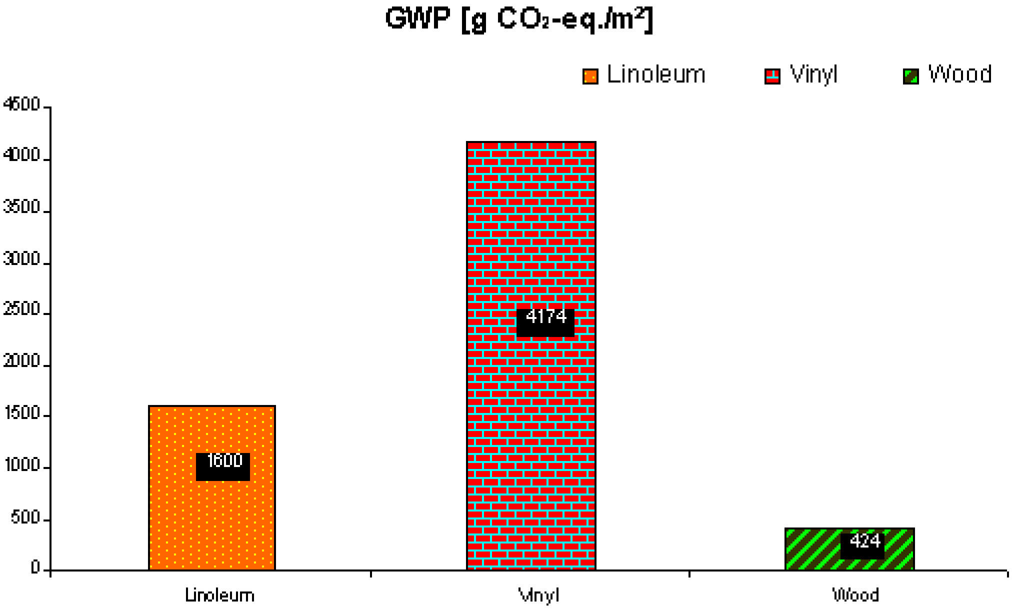


Figure 31: Global warming potential related to 1 m² of flooring material

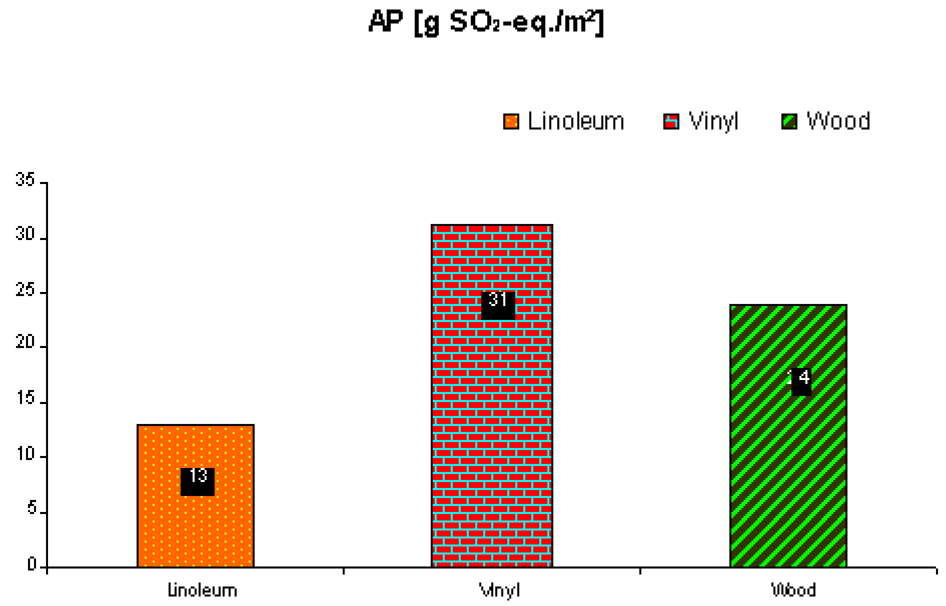


Figure 32: Acidification potential related to 1 m² of flooring material

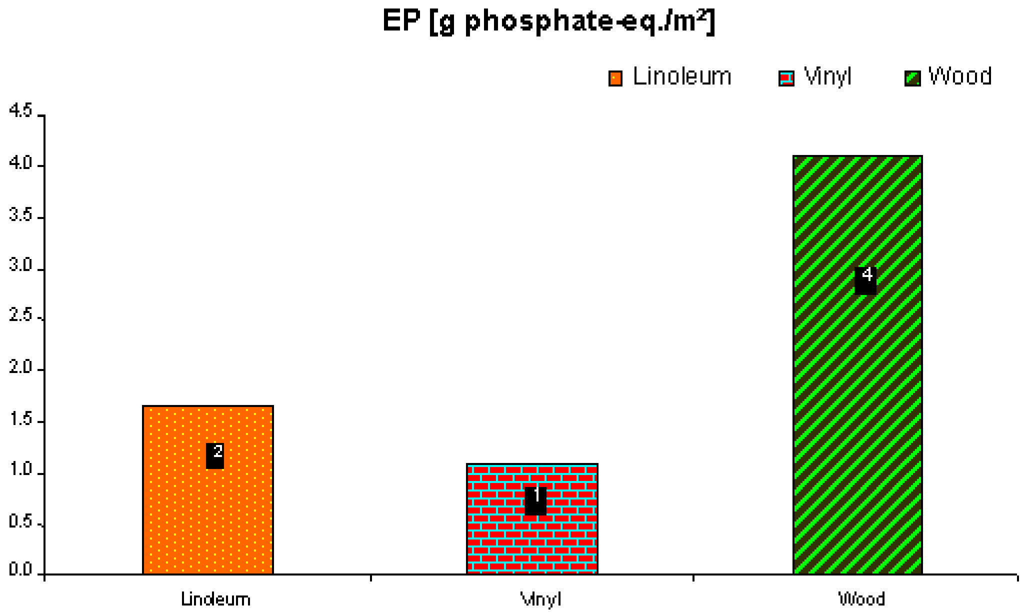


Figure 33: Eutrophication potential related to 1 m² of flooring material

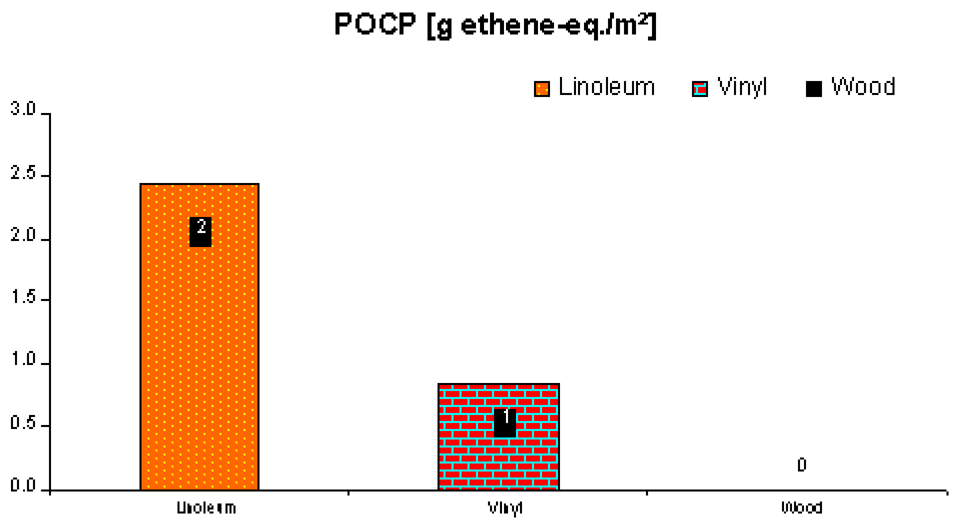


Figure 34: Photochemical ozone creating potential related to 1 m² flooring material

As can be seen from Tables 15, 16 and 17, waste and dust are two environmental loads considered in the flooring study of Åsa Jönsson (1995) where waste is divided into "ash", "sector-specific waste" and "hazardous waste". The results obtained lead to the following conclusions:

• PVC shows the highest load with respect to the content of ash and sector-specific waste (Figure 35).

• Regarding the hazardous waste, linoleum dominates but PVC also contains a considerable amount (121 g/m²) of hazardous waste (Figure 35).

• Wood contains neither sector-specific waste nor hazardous waste. Its ash content is also very small and amounts to 172 g/m³ (Figure 35). It is, therefore, the best environmentally sound material among the flooring materials investigated and it does not cause human toxicity and eco-toxicity.

• Dust can have toxic effects on human beings and the amount in wood flooring is very small (1.2 g/m²). In the case of linoleum and PVC, the dust emissions are 34.5 g/m² and 6.8 g/m², respectively.

Åsa Jönsson *et al.* (1995) concluded that according to the results, solid wood flooring proved to be environmentally the best flooring followed by linoleum and PVC.

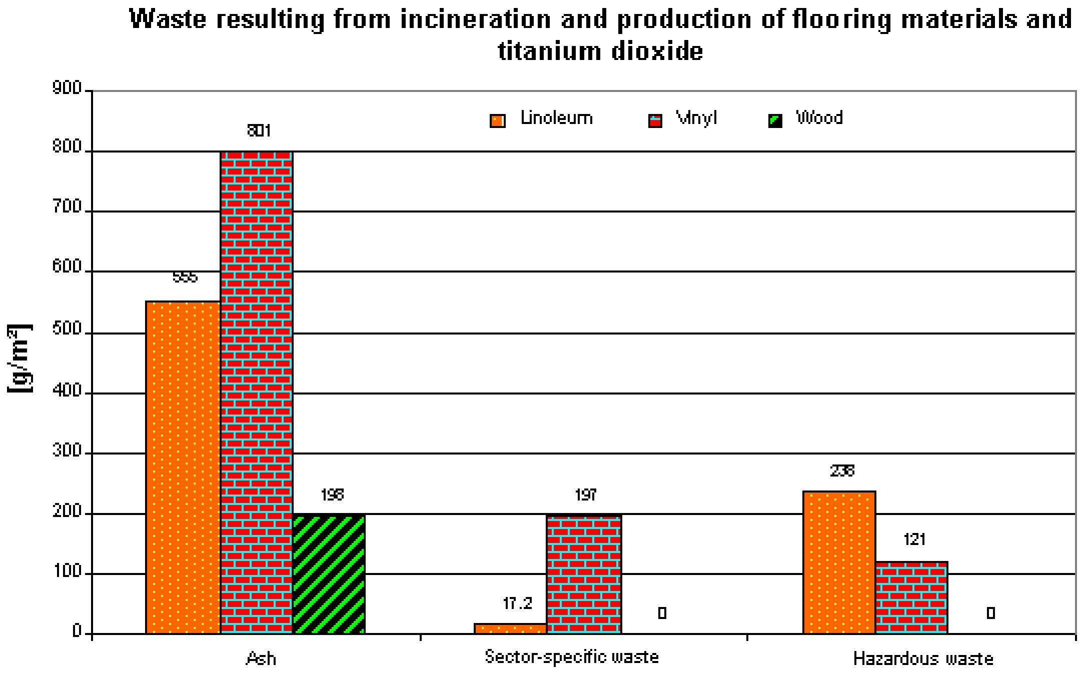


Figure 35: Waste amount related to 1 m² of flooring material

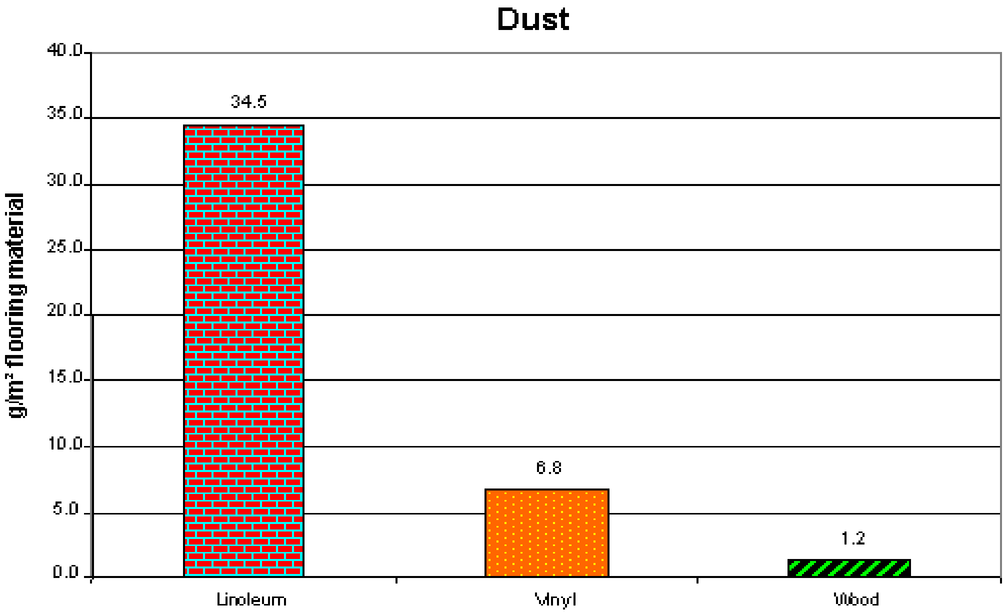


Figure 36: Dust related to 1 m² of flooring material

Parquet

Definition of products and method

Werner and Richter (1997) conducted a comprehensive study on the LCA of wood flooring. The applied method differs from that of Åsa Jönsson (1995) and is in accordance with the LCA standard ISO/EN 14040. The three different parquet types for normal use which were studied are:

- mosaic solid parquet, glued;
- two-layer prefabricated parquet, glued; and
- three-layer prefabricated parquet, glued.

The life cycle phases (modules) analysed are preliminary stage raw wood, parquet production, packaging, delivering, laying, sealing, renovation 1, renovation 2 and demolition. The results obtained for LCI and impact assessment are related to 1 m² of parquet (functional unit) and the lifetime is considered to be 45 years. For more details see Werner and Richter (1997).

Comparison between the parquet types

The results of energy analysis are found in Table 18, from which can be seen that energy consumption for "mosaic solid parquet", "two-layer prefabricated parquet" and "three-layer prefabricated parquet" amounts to 314 MJ/m², 402 MJ/m², and 582 MJ/m², respectively. The renewable energy is generated from wood residues and the impact potentials are based on the BUWAL study (1990). The share of renewable energy is in the same order, 30 percent, 31 percent and 52 percent of total energy consumption. The differentiation of energy consumption based on modules mentioned above is shown in Appendices 2, 3 and 4.

Table 18: Energy consumption related to 1 m² of parquet

	Non-renewable energy	Renewable energy	**Total energy**
	(MJ)	(MJ)	**(MJ)**
Mosaic solid parquet, glued	219.14	94.85	**314**
Two-layer prefabricated parquet, glued	278.17	123.53	**402**
Three-layer prefabricated parquet, glued	280.49	301.64	**582**

The environmental impact potentials are calculated separately for renewable and non-renewable energy consumed for production of 1 m² of parquet. The results illustrated in Figures 37, 38, 39 and 40 demonstrate:

- Increasing energy consumption results in the increase of impact potentials and the mosaic solid parquet is specified as the most environmentally sound flooring.

- Increase of renewable energy leads to an overproportional reduction of the environmental impacts (Table 19).

Table 19: Energy and the resulting environmental impacts

	Ratio of RE to NRE[a)]	Ratio of impacts of RE to impacts of NRE		
		GWP	AP	EP
Mosaic solid parquet, glued	0.43	0.001	0.12	0.21
Two-layer prefabricated parquet, glued	0.44	0.001	0.13	0.22
Three-layer prefabricated parquet, glued	1.07	0.002	0.29	0.52

a) RE = renewable energy, NRE = non-renewable energy

- For the two-layer and three-layer prefabricated parquet the consumption of non-renewable energy and the resulting impact potentials are almost the same and these can be reduced by increasing renewable energy and decreasing the non-renewable energy.

- Attention should also be paid to the environmental effects caused by renewable energy. Between mosaic solid parquet and two-layer prefabricated parquet the differences of GWP, AP and EP are smaller than between two-layer and three-layer prefabricated parquets.

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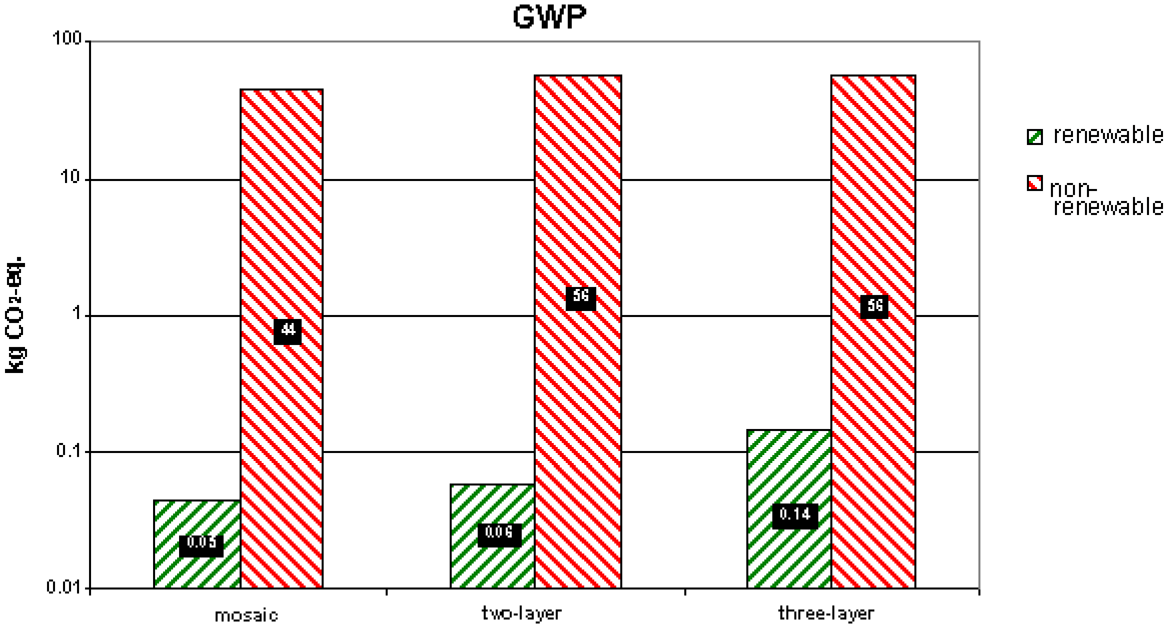


Regarding POCP, the renewable energy is less favourable than non-renewable energy but the absolute values are too small and might not have serious effects.

Figure 37: Logarithmic illustration of GWP for different parquet types

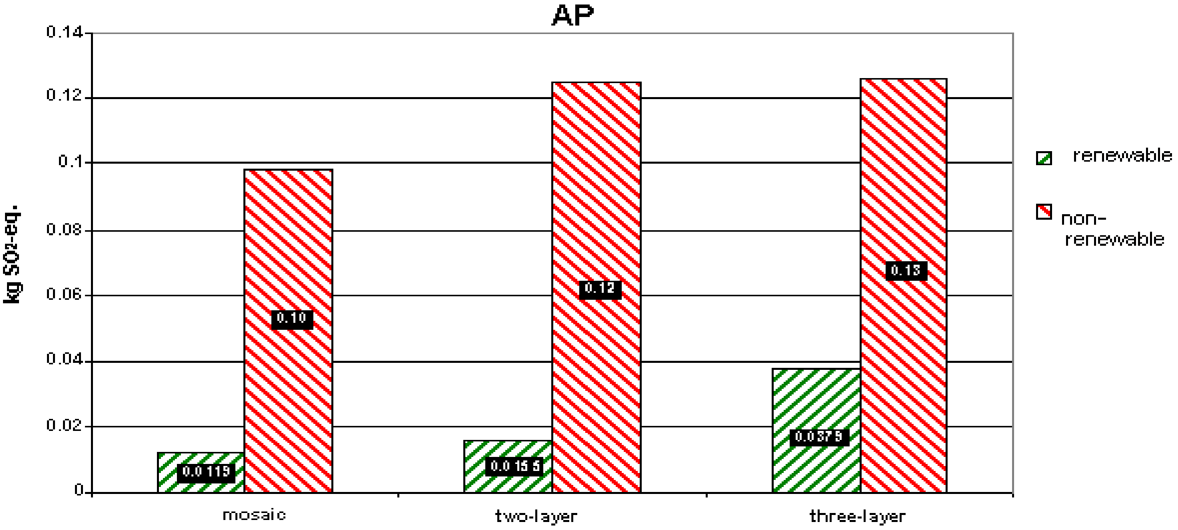


Figure 38: Logarithmic illustration of AP for different parquet types

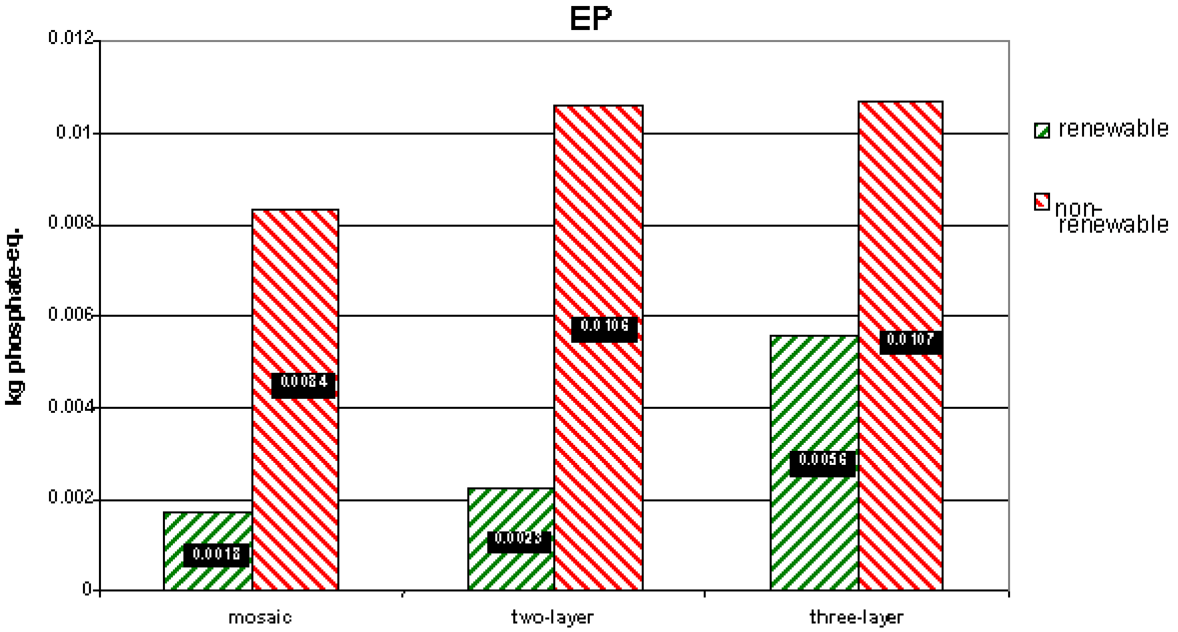
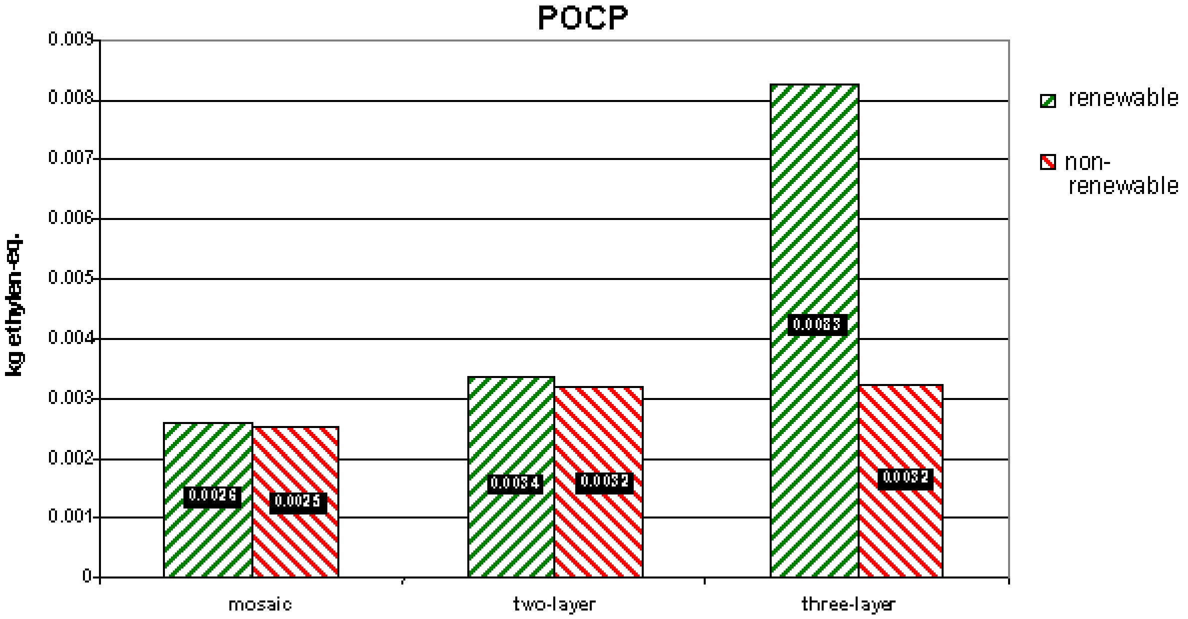


Figure 39: Eutrophication potential for different parquet types

Figure 40: POCP for different parquet types



4 Normal level is described in Appendix 1.

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