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EXERGY AND SUSTAINABILITY

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Abstract

A thorough qualitative investigation of the relation between exergy losses and environmental problems has been conducted. Environmental effects being taken into account include climate change, acidification, eutrophication, disposal and dissipation. It is concluded that almost all environmental effects can be taken into account by studying the waste of feedstocks and energy caused by technological activities, like processes, and the emission and dispersion of pollutants. To underpin the qualitative investigation two case studies have been conducted: the production of aluminium and polystyrene. On the basis of the results of the case studies it can be made plausible that exergy losses and environmental impact are related. Exergy losses are a kind of environmental impact, whereas environmental impact is related to exergy loss. It is concluded that exergy loss is at least a qualitative measure that can be used in environmental policy making regarding technological processes. According to literature, exergy losses should be minimized to obtain a more sustainable development. During a follow-up study the relation between exergy and sustainability will be investigated in more detail, partly based on basic principles borrowed from nature. Apart from environmental impact also others aspects of sustainability, like economic and social aspects, will be taken into account.

Introduction

Many options exist for energy supply, transport fuels, technological products and processes and other activities. In the interest of sustainable development it is important to make the right choices. The Dutch ministry of Housing, Spatial Planning and the Environment wanted to know whether exergy is a measure of the environmental impact caused by feedstock use, energy use and emissions, because such a measure could be used in environmental policy making. The research consists of two parts: a qualitative investigation of the relation between exergy and all kinds of questions related to environmental policy making, followed by analysis of two case studies: the production of aluminium and polystyrene.

Qualitative investigation

The environmental impact of human activities has many aspects, like climate change (global warming, ozone depletion), acidification, eutrophication, disposal, dissipation,

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disturbance and waste (depletion of energy and abiotic resources). This environmental impact can be traced back to the use of feedstocks and energy, and the emission and dispersion of pollutants [1]. From the viewpoint of environmental policy making it is relevant to know whether the environmental impact caused by feedstock use, energy use and emissions can be expressed in one measure: exergy. Other interesting aspects are the relation between exergy and spatial dissipation of materials, at what level of aggregation, e.g. materials, chains, networks, to apply the concept of exergy, and the usefulness of exergy in the determination of unnecessary environmental impact and inefficiencies. During the qualitative investigation all kinds of questions related to environmental policy making and the concept of exergy have been considered.

It was concluded from this investigation that almost all environmental effects can be taken into account by studying the waste of feedstocks and energy caused by technological activities, like processes, and the emission and dispersion of pollutants. A careful consideration of system boundaries is important, especially when comparing processes or materials, because in many cases it will be necessary to take into account additional processes or units to ensure the comparability of the alternatives. It is common knowledge between thermodynamicists that every (technological) process is accompanied by exergy loss. However the depletion of natural resources like feedstocks and energy carriers is a fact, not a process, therefore depletion cannot be expressed in terms of exergy loss. The same holds for the harmfulness, e.g. toxicity, of waste emissions. It can be argued that the more harmful the waste emission the more stringent the standards for this emission, and that there is no need to take into account emissions that meet their standards. It can also be said that the scarcer the resource, the more difficult the extraction of that resource and the higher the exergy loss caused by that extraction.

Some authors [2, 3] state that the depletion of exergy, not the depletion of resources, should be minimised to obtain sustainable development. They refer to the concept of Cumulative Exergy Consumption (CExC) [4] and recommend extending the Life Cycle Assessment methodology with the determination of exergy losses (Exergetic LCA or ELCA). It is also being said [5] that “exergy can be considered the confluence of energy, environment and sustainable development” and that “exergy methods can be used to improve sustainability”. According to the authors order destruction and chaos creation, as well as resource degradation and waste exergy emissions decrease with increasing process exergy efficiency. In [6] the potential and limitations of exergy in environmental science and technology are reviewed. It is said that in several cases it may make sense to assess the impact of emissions by taking into account the exergy loss caused by abatement of the emissions, but that this exergy loss does not reflect the environmental impact of the emissions. According to the authors the by far most applied method for assessing the intake of resources is CExC.

A careful underpinning of the relation between exergy loss and environmental impact has not been found in literature. To investigate whether exergy loss is a measure of the environmental impact of processes the exergy losses caused by the production of aluminium and polystyrene have been compared with the environmental effects of these production processes.

Case study aluminium

The production of aluminium from bauxite ore is called primary production of aluminium and is depicted in Fig. 1. The remaining part of bauxite after alumina (Al_2O_3) separation consists of sand and metal (ferro) compounds and is called 'red mud' because of its red colour. Aluminium can also be produced from aluminium waste, the so-called secondary production.

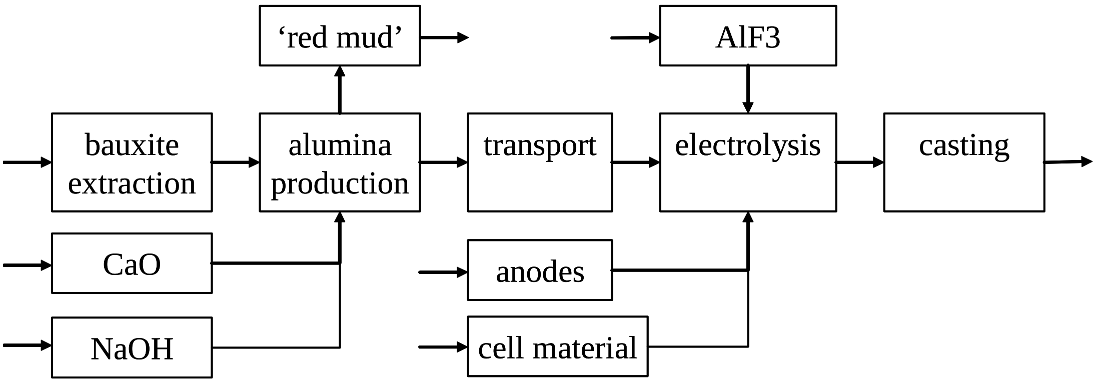

Fig. 1: *Primary production of aluminium.*

The data used in this case study originate from [7-9]. The environmental impact caused by the primary production of aluminium is presented in Tables 1 to 4. Only emissions larger than 10 kg per ton of end product are presented.

[kg/ton aluminium]	*bauxite extraction*	*alumina production*	*transport*	*electrolysis*	*casting*
bauxite (ore)	19152	4788			
CaO		87			
NaOH		429			
alumina				1900	
AlF_3				18	
anodes				430	
cell material				9	
aluminium					1000
Total	19152	5304	0	2357	1000

Table 1: *Feedstock use in primary production of aluminium (global numbers).*

[GJ/ton aluminium]	*bauxite extraction*	*alumina production*	*transport*	*electrolysis*	*casting*
electricity	0.03	1.6		54	2.1
heavy fuel oil	2.5	16	10		2.9
extra light fuel oil				3.8	
natural gas					1.3
Total	2.6	18	10	58	6.3
[% of total]	*3*	*19*	*11*	*61*	*7*

Table 2: *Energy use in primary production of aluminium (global numbers).*

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[kg/ton aluminium]	*bauxite extraction*	*alumina production*	*transport*	*electrolysis*	*casting*
CO_2				898	
waste water	599	9481			15269
soil	14361				
SO_2			12	8	
COD		19			
'red mud'		2888			
solid waste		516			
CO				444	
hydrocarbons					
NO_x				3	

Table 3: *Emissions due to primary production of aluminium excluding chain effects (global numbers).*

[kg/ton aluminium]	*bauxite extraction*	*alumina production*	*transport*	*electrolysis*	*casting*
CO_2	203	1605	818	11008	678
waste water	599	10471			15269
soil	14361				
SO_2		13	20	24	
COD		19			
'red mud'		2888			
solid waste		575		1188	47
CO				445	
hydrocarbons				94	
NO_x				23	

Table 4: *Emissions due to primary production of aluminium including chain effects (global numbers).*

The exergy losses due to the primary production of aluminium are presented in Table 5. These exergy losses have been calculated by applying the standard exergy values from [10]. The internal and external exergy losses of each process unit have been calculated, as well as the exergy losses caused by the production of feedstocks and utilities needed in the process units, the so-called chain effects.

[GJ/ton aluminium]	*bauxite extraction*	*alumina production*	*transport*	*electrolysis*	*casting*
internal	2.4	19	0.4	43	6.2
external	0.1	1.9	0.06	0.5	2.6
subtotal	2.5	21	0.5	43	8.9
[% of total]	*3*	*28*	*<1*	*57*	*12*
chain effects	0.3	7.4	0.5	180	7
Total	2.8	28	1.0	223	16
[% of total]	*1*	*11*	*<1*	*82*	*6*

Table 5: *Exergy losses due to primary production of aluminium*
(excluding and including chain effects, global numbers).

When the exergy losses excluding chain effects from Table 5 are compared with the energy use in Table 2, it appears that the distribution of exergy losses across the

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various process units is comparable to the energy used in the process units. This could be explained by the low energy value, and thus low exergy value, of the feedstocks. The amount of feedstock used decreases along the production chain of aluminium (see Table 1), but this does not apply to the exergy loss. The exergy loss of a process unit depends on the kind of transition taking place, i.e. physical or chemical. A reason why feedstock use and exergy loss are not comparable, could be the relatively low exergy value of the feedstocks.

According to Tables 3 and 4, the production of alumina causes a large amount of 'red mud'. The high CO_2 emission due to electrolysis is notable as well. It is unknown whether these emissions meet the standards. Electrolysis and alumina production cause the highest emissions as well as the highest exergy losses (see Table 5), which implies that the calculated exergy losses point in the right direction regarding the environmental impact caused by emissions. However, as explained before, the harmfulness of waste emissions cannot be expressed in terms of exergy loss.

Case study polystyrene

Polystyrene is produced from crude oil as depicted in Fig. 2. During alkylation/dehydrogenation benzene is alkylated with ethylene to ethylbenzene, followed by dehydrogenation of ethylbenzene to styrene.

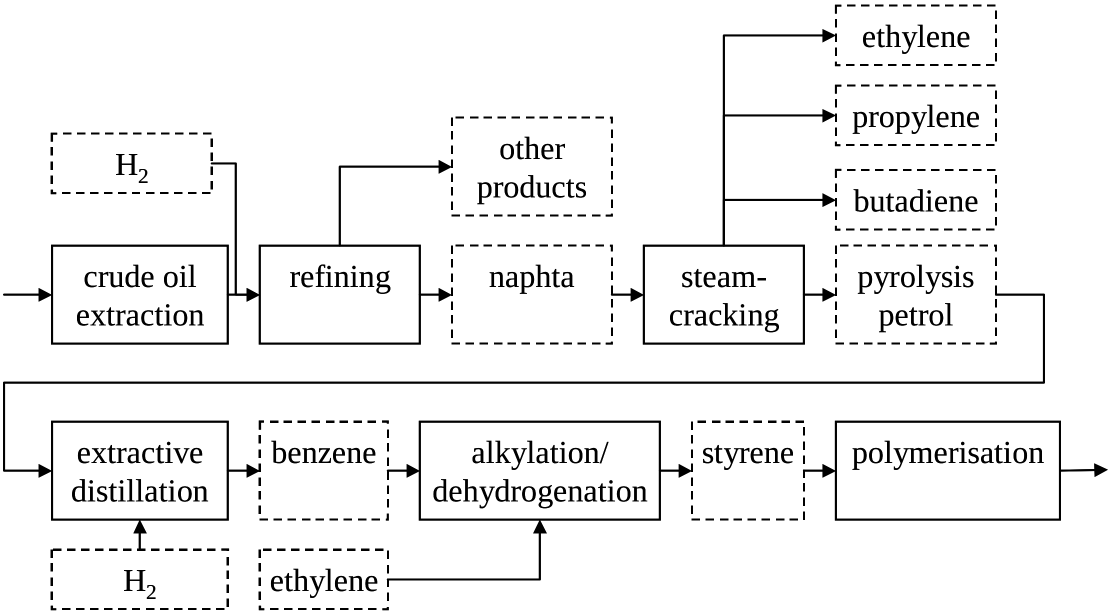

Fig. 2: *Production of polystyrene.*

The data used in this case study originate from [7, 11, 12]. The environmental impact caused by the production of polystyrene is presented in Tables 6 to 9.

[kg/ ton PS]	*crude oil extraction*	*refining*	*steam cracking*	*extractive distillation*	*alkylation/ dehydrog.*	*polyme-risation*
crude oil	1551	1524				
naphta			1449			
pyrolysis petrol				791		
hydrogen				4		
benzene					795	
ethylene					292	
styrene						975
other					7	31
Total	1551	1524	1449	795	1094	1006

Table 6: *Feedstock use in production of polystyrene (global numbers).*

[GJ/ ton PS]	*crude oil extraction*	*refining*	*steam cracking*	*extractive distillation*	*alkylation/ dehydrog.*	*polyme-risation*
electricity	0.1	0.06	0.1	0.01	0.3	0.9
natural gas	0.2		7.2			
heavy fuel oil	0.01	3.7			6.5	
steam				1.5	7.8	1.1
Total	0.4	3.8	7.4	1.5	15	2.0

Table 7: *Energy use in production of polystyrene (global numbers).*

[kg/ ton PS]	*crude oil extraction*	*refining*	*steam cracking*	*extractive distillation*	*alkylation/ dehydrog.*	*polyme-risation*
dissolved solids	19					
solid waste			72			

Table 8: *Emissions due to production of polystyrene excluding chain effects (global numbers).*

[kg/ ton PS]	*crude oil extraction*	*refining*	*steam cracking*	*extractive distillation*	*alkylation/ dehydrog.*	*polyme-risation*
CO_2	35	302	23		1047	232
dissolved solids	19					
solid waste			75			20

Table 9: *Emissions due to production of polystyrene including chain effects (global numbers).*

The exergy losses due to the primary production of polystyrene are presented in Table 10. These exergy losses have been calculated by applying the standard exergy values from [10]. The internal and external exergy losses of each process unit have been calculated, as well as the exergy losses caused by the production of feedstocks and utilities needed in the process units, the so-called chain effects. Also the avoided exergy losses by the production of valuable by-products (credits by-products) have been taken into account.

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[GJ/ton PS]	*crude oil extract.*	*refining*	*steam cracking*	*extract. distill.*	*alkyl./ dehydr.*	*polymerisation*
internal	1.5	0.1	1.9	0.07	1.7	0.5
external	0.04	0.06	8.6	0.00	0.05	0.01
subtotal	1.5	0.2	11	0.07	1.7	0.5
[% of total]	*11*	*1*	*72*	*<1*	*12*	*4*
chain effects						
- prod. feedst. & utilities	0.4	0.5	1.0	2.2	12	4.4
- credits by-products	-0.00	-0.3	-2.9	-2.3	-0.3	-0.01
Total	1.9	0.5	8.6	0.02	14	5.0
[% of total]	*7*	*2*	*29*	*<1*	*46*	*17*

Table 10: *Exergy losses due to production of polystyrene*
(excluding and including chain effects, global numbers).

Looking at the environmental impact of the process units including chain effects (Tables 6 to 9), the high energy use and large amount of CO_2 emitted in alkylation/dehydrogenation are notable. According to Table 10 also most of the exergy is lost during alkylation/dehydrogenation including chain effects. Steam cracking is considered to be the process unit with the second most environmental impact because of its relatively high energy use and the amount of solid waste. Steam cracking is the process unit with the second most exergy loss as well. From this it may be concluded that exergy analysis points out the process units with the highest environmental impact.

Discussion and conclusions

According to the qualitative investigation almost all environmental effects can be taken into account by studying the waste of feedstocks and energy caused by technological activities, like processes, and the emission and dispersion of pollutants. The depletion of natural resources and the harmfulness of waste emissions cannot be expressed in terms of exergy loss. However, it is expected that the scarcer the resource, the more exergy is lost during extraction of that resource, and the more harmful an emission, the more stringent the standards for this emission and the higher the exergy loss accompanied with meeting these standards.

It appeared difficult to underpin the results of the qualitative investigation by conducting the two case studies. The difficulty in investigating whether exergy is a measure of the environmental impact caused by feedstock use, energy use and emissions, is the lack of such a measure to compare exergy loss with.

In a qualitative way it could be made plausible that exergy loss is accompanied with environmental impact. The other way round, i.e. that a higher environmental impact implies a higher exergy loss, can be understood but could not be convincingly underpinned on the basis of the case studies. Maybe this could be done by carrying out case studies on a lower level of aggregation, e.g. not on the level of production chains but on the level of process units.

On the basis of the results of the cases studied it can be made plausible that exergy losses and environmental impact are related. Exergy losses are a kind of environmental impact, whereas environmental impact is related to exergy loss. It is concluded that exergy loss is at least a qualitative measure that can be used in environmental policy making regarding technological processes.

Future research

During a follow-up study the relation between exergy and sustainability will be investigated in more detail, partly based on basic principles borrowed from nature. Apart from environmental impact also other aspects of sustainability, like economic and social aspects, will be taken into account.

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References

1. L. Stougie et al., “Entropy or exergy – a measure in environmental policy making?” (in Dutch), (Delft University of Technology, 1994).
2. R.L. Cornelissen, “Thermodynamics and sustainable development – The use of exergy analysis and the reduction of irreversibility”, (Ph.D. Thesis, Twente University, 1997).
3. J.C. Boudri et al., “Study after the added value of exergetic LCA compared to LCA” (in Dutch), (2EWAB00.32, Novem, Utrecht, 2000).
4. J. Szargut, D.R. Morris & F.R. Stewart, *Exergy analysis of thermal, chemical, and metallurgical processes*, (Hemisphere Publishing Corporation, New York, 1988).
5. I. Dincer, M.A. Rosen, *Exergy: Energy, Environment and Sustainable Development*, (Elsevier Ltd, Amsterdam, 2007).
6. J. Dewulf et al., “Exergy: Its Potential and Limitations in Environmental Science and Technology”, *Environmental Science & Technology*, **42** (2008) 2221-2232.
7. K. Habersatter, “Oekobilanz von Packstoffen stand 1990”, (Schriftenreihe Umwelt Nr. 132, BUWAL, Bern, 1991).
8. SAC (Aluminium Center, http://www.aluminiumcentrum.nl), “Aluminium, a good material for packaging” (in Dutch), (910412, Woerden).
9. SPIN (Cooperation project process descriptions Dutch industry, http://www.rivm.nl), “Production of primary aluminium” (in Dutch), (RIVM 736301108, Bilthoven, 1992).
10. T.J. Kotas, *The Exergy Method of Thermal Plant Analysis*, (Butterworths, London, 1988).
11. A. Chauvel, G. Lefebvre, *Petrochemical Processes Vol. 1, Technical and Economic Characteristics*, (Texas, 1989).
12. H.G. Franck, J.W. Stadelhofer, *Industrial Aromatic Chemistry: Raw Materials, Processes, Products,* (Springer-Verlag, Berlin, 1988).