LCA Methodology

The Environmental Relevance of Capital Goods in Life Cycle Assessments of Products and Services *

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Abstract

Goal and Scope. Many life cycle assessment case studies neglect the production of capital goods that are necessary to manufacture a good or to provide a service. In ISO standards 14040 and 14044 the capital goods are explicitly part of the product system. Thus, it is doubtful if capital goods can be excluded per se as has been done in quite a number of case studies and LCA databases. There is yet no clear idea about if and when capital goods play an important role in life cycle assessments. The present paper evaluates the contribution of capital goods in a large number and variety of product and service systems. A classification of product and service groups is proposed to give better guidance on when and where capital goods should be included or can be neglected.

Methods. The life cycle inventory database ecoinvent data v1.2 forms the basis for the assessment of the environmental importance of capital goods. The importance is assessed on the basis of several hundreds of cradle-to-gate LCAs of heat and electricity supply systems, of materials extraction and production, of agricultural products, and of transport and waste management services. The importance within product (and service) groups is evaluated with statistical methods by comparing the LCA results including and excluding capital goods. The assessment is based on characterised cumulative LCI results using the CML baseline characterisation factors of the impact categories of global warming, acidification, eutrophication, human toxicity, freshwater acquatic toxicity, terrestrial ecotoxicity, ionising radiation, and land competition, based on proxy indicators (fossil and nuclear) cumulative energy demand, and based on the endpoint indicators Eco-indicator 99 (H,A) mineral resources, human health, eco system quality and totals.

Results. The analysis confirms the fact that capital goods cannot be excluded per se. On one hand, toxicity related environmental impacts such as freshwater ecotoxicity or human toxicity are more sensitive towards an inclusion or exclusion of capital goods. On the other, certain products like photovoltaic and wind electricity are very much or even completely affected by capital goods contributions, no matter which indicator is chosen. Nuclear electricity, agricultural products and processes, and transport services often behave differently (showing a higher or lower share of capital goods contribution) than products from other sectors.

Discussions. Some indicators analysed in this paper show a rather similar behaviour across all sectors analysed. This is particularly true for 'mineral resources', and – to a lesser extent – for 'Eco-indicator 99 total', 'acidification' and 'climate change'. On the other hand, 'land use' and 'freshwater ecotoxicity' show the most contrasting behaviour with shares of capital goods' impacts between less than 1% and more than 98%.

Recommendations. Capital goods must be included in the assessment of climate change impacts of non-fossil electricity, agricultural products and processes, transport services and waste management services. They must be included in any sector regarding the assessment of toxic effects. Energy analyses (quantifying the non-renewable cumulative energy demand) of agricultural products and processes, of wooden products and of transport services should include capital goods as well.

The mixing of datasets including and excluding capital goods is no problem as long as their share on total impacts is low and partial omissions do not lead to a significant imbalance in comparative assertions.

Perspectives. If in doubt whether or not to include capital goods, it is recommended to check two things: (1) whether maintenance and depreciation costs of capital equipment form a substantial part of the product price (Heijungs et al. 1992a), and (2) whether actual environmental hot spots occur along the capital goods' supply chain.

Keywords: Capital goods; ecoinvent database; environmental relevance; infrastructure; life cycle assessment; life cycle inventory data; products and services

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Introduction, Problem Setting and Goal

Many life cycle assessment case studies neglect the production of capital goods that are necessary to manufacture a good or to provide a service. Several publications in the scientific literature deal with the aspect of relevance of capital goods and infrastructure. One of the reference works on energy analysis states: "Although capital energy is usually a relatively small contributor to total system energy requirement, this is not always so. In situations where machines operate under particularly arduous and demanding conditions, the lifetime of the machines or parts of the machines may be very short indeed" (Boustead & Hancock 1979, p. 179). According to them, the capital energy contribution is usually on the order of 5%. Hence, omitting capital equipment would result in an error of 5%. They consider it clear that even with a very crude estimate of capital energy this small error will be significantly reduced (Boustead & Hancock 1979, p. 120). During the life cycle assessment workshop held in 1991 in Leiden, the Netherlands, there was agreement that capital goods should be included in a comparative LCA of two processes in which the amount of investments would be clearly and significantly different (Huisingh 1992).

Heijungs et al. (1992a, p. 28) state that it is difficult to say which processes may be excluded and when and that practical studies will have to demonstrate whether rules of thumb can be given or not. With regard to capital good they suggest identifying the production of capital goods as 'pro memoria' items in cases where they are not included in the product system. In the ISO standards 14040 and 14044 (International Organization for Standardization (ISO) 2005a, b), the capital goods are explicitly part of the product system. Hence, the standard cut-off criteria mass, energy and environmental relevance apply on capital goods like on any other input. Guinée et al. (2001b) emphasise the definition problem, because the object of investigation in one study may well be the capital good in another one. Think of the life cycle assessment concerning the production of different types of piping systems, on one hand, and of different supermarket cooling systems, where piping systems are part of the capital goods required to supply the service, on the other. That is why they recommend that the same rules be applied for the cut-off of capital goods as for any other input or output flow.

The content of life-cycle inventory databases differs with regard to the inclusion or exclusion of infrastructure and capital goods. The BUWAL LCI data on packaging developed by ETHZ/Empa explicitly exclude capital equipment because of high demands in terms of time and work for the packaging industry representatives and, at the same time, due to the expected low contribution to the total environmental impacts (Habersatter et al. 1998, vol. I, p. 32). In contrast to that, the energy systems database developed at ETHZ/PSI (Frischknecht et al. 1996, Frischknecht et al. 1994) and its successor, the ecoinvent database v1.2 (ecoinvent Centre 2006), systematically include capital equipment.

Hence, it is still unclear whether or not capital goods can be excluded or must be included. This paper gives an answer to this question. In Section 1, the scope of analysis is described and 'capital goods', as applied in the assessed data, are given. In Section 2, the results of the assessment of a large number of life cycle inventory datasets are presented. The assessment includes electricity supply, materials production, agricultural products and processes, as well as transport and waste treatment services. The final section, Section 3, includes conclusions and recommendations on how to deal with capital equipment in future LCA studies.

1 Scope Definition

Most online dictionaries define capital goods as 'goods', such as machineries, used in the production of commodities (articles of trade or commerce); producer goods'[1]. It can be a personal computer used to supply LCA consulting services, an industrial building to produce gas turbines (or parts of it), a road that serves for transport service companies, or electricity networks that transport electricity to the customers. Reality in life cycle inventory (LCI) modelling does not always fit easily to the definition cited above. This is illustrated with two examples.

Boreholes are drilled to explore a new oil field and during continuous oil extraction operations. On the one hand, boreholes could be considered as an operation like pumping and dewatering of oil, because they are manufactured continuously during oil production activities. On the other hand, boreholes can be considered as a 'capital equipment', because they are a means of production required to enable oil production. The question becomes whether or not oil wells should be classified as a 'capital good' input or as a working material and, thus, an 'operation' input.

Primary aluminium is produced using a prebaked or Söderberg anode (made of petroleum coke and coal-tar pitch). The anode must be replaced periodically as it is used up during production. Also here, the question becomes whether or not to classify the anode as a working material or part of the capital equipment.

The present paper explores the question whether or not, and if yes, in which cases, capital goods shall be included in life cycle assessments. To be able to do that a workable and pragmatic and operational implementation of the definition cited above is required. The ecoinvent database implemented such a distinction on the level of each individual unit process dataset. All processes are separated in a dataset into the 'operation' and the 'capital good' required for this operation. Datasets are classified as either 'operation' or 'capital goods' with the help of a Yes/No entry in the EcoSpold data field No. 493 'InfrastructureProcess' (Yes = capital good, No = operation). The operation dataset, which produces the traded product (such as sawed timber, for instance) asks for a certain (in most cases tiny) amount of capital goods (such as a sawmill and sawing machinery).

In a few cases, the classification to either capital good or operation is not straightforward. One example, involving the drilling and manufacturing of oil and gas boreholes as one of them, is which is classified as a capital equipment in the ecoinvent database. The land use of a landfill is classified as 'operation' similar to the land use of open pit mines

[1] Dictionary definition of capital goods: The American Heritage® Dictionary of the English Language, Fourth Edition Copyright © 2004, 2000 by Houghton Mifflin Company. Published by Houghton Mifflin Company. All rights reserved.

and of agricultural production. Within the transportation sector, the operation, maintenance and disposal of road, railway, and harbour infrastructures are classified as 'capital goods' unit processes. The construction of factories used to manufacture chemicals, metals, solar cells, et cetera is classified as capital goods as well. In contrast, the operation of those factories (i.e. the manufacturing process of chemicals, metals, solar cells, et cetera) is classified as 'operation'. The production of the machinery used in agriculture is classified as 'capital equipment', whereas its use on the field for mowing, baling and the like is classified as 'operation'.

The ecoinvent software system is able to compute cumulative LCI and LCIA results including or excluding the contributions to resource consumption and emissions from capital goods. Hence, the product system of one and the same product can differ with regard to the scope: In one case it only includes the 'operation' aspects of process chains. In a second case, capital goods required to run the processes are included as well.

The two results (once including, once excluding capital goods) are compared and the share of capital goods is determined as shown in **Eq. (1)**:

$$CG_i = \frac{LCIA_i^{incl} - LCIA_i^{excl}}{LCIA_i^{incl}} \qquad (1)$$

with CG_i being the share of capital goods on the cumulative results of impact category indicator (or cumulative weighted results) i, $LCIA_i^{incl}$ is the cumulative results of impact category indicator (or cumulative weighted results) *i including* capital goods and $LCIA_i^{excl}$ is the cumulative results of impact category indicator (or cumulative weighted results) *i excluding* capital goods. A share of 100% means that the cumulative environmental impacts of a product are exclusively caused by capital goods manufacturing. This, for instance, is the case in photovoltaic electricity production where the impacts during operation are negligible. A share close to 0% indicates a negligible relevance of capital goods.

The ecoinvent database system relies on a matrix calculation approach (Frischknecht & Kolm 1995, Heijungs et al. 1992b, p. 52ff., Heijungs & Suh 2002). The product systems consist of a large number of gate-to-gate unit processes. Each unit process dataset is itself classified either as 'capital good' or as 'operation'. Some of the inputs of each unit process dataset are classified 'capital good', the remaining ones are classified 'operation'. In the calculation of cumulative results of product systems with capital goods excluded, every input of a 'capital goods' dataset into a unit process dataset is set to zero and consequently cut off ('car manufacture' and 'road construction' in **Fig. 1**). In other words, the system boundary excludes those parts of the product system that are linked to 'capital goods' inputs. Some of the unit processes within those excluded parts of the product system may well be 'operation' unit process datasets (e.g. 'diesel, in machine' or 'electricity, at plug' in Fig. 1). But they contribute to the manufacture of capital equipment and are thus excluded. In the calculation of cumulative results excluding 'capital goods', 'operation' inputs such as 'electricity, at plug' are excluded at all levels of capital goods

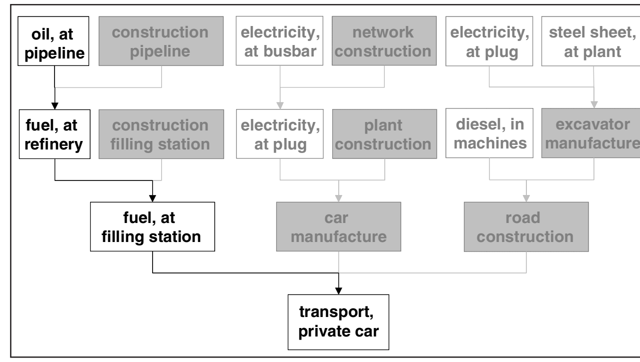

Fig. 1: Flow chart of a simplified product system of transport service provision by private car, including capital good manufacturing. When capital good manufacturing is excluded, only the unit processes in dark black are considered ('transport, private car', 'fuel, at filling station', 'fuel, at refinery', 'oil, at pipeline'). All remaining unit processes displayed semi-transparently are cut-off; white: operations' datasets; grey shaded: capital goods' datasets

supply, be it the manufacture of the car, the construction of the road or the manufacture of the excavator used to build the road.

Hence, two substantially different product systems result depending on whether or not 'capital goods' datasets are included:

PS^{incl}: product system *including* capital goods manufacture (all boxes in Fig. 1)

PS^{excl}: product system *excluding* capital goods manufacture (dark black boxes in Fig. 1)

The two differing product systems include minerals extraction and energy supply chains up to the mine and oil well, respectively, and production waste management services down to the grave. The difference is that PS^{excl} only includes mining, refining, manufacturing, transport and waste management processes that are required by the operation and excludes those required by the capital goods required to run the process. In other words, operation datasets (such as the production of electricity in a power plant) are excluded if they are used in capital goods' manufacture (e.g. the construction of a building machine or a road). Catalysts are classified as working materials and registered within the operation of processes (such as the refining of oil). In some cases (landfills with regard to the indicator 'land use'), these particular decisions on the distinction between operation and capital goods manufacture influence the results shown below. However, the results are in general not dependent on these few ambiguous decisions.

Several impact category indicators are selected to cover the broad range of potential environmental impacts. The analysis is performed with three types of indicators (**Table 1**, see overleaf), proxy indicators based on the cumulative energy demand (Frischknecht et al. 2004), mid-point indicators based on the CML characterisation profiles (Guinée et al. 2001a) and the global warming potentials of IPCC (IPCC 2001) and end-point indicators based on the Eco-indicator 99 (Goedkoop & Spriensma 2000).

For better readability, the various proxy, impact category and assessment indicators are just called 'indicators' in the following section.

Table 1: List of impact assessment indicators applied on the life cycle inventory results to assess the importance of infrastructure and capital goods contributions. The methods are implemented into the ecoinvent database according to Frischknecht et al. (2004)

	Name	Unit	Source
Proxy indicators	**Cumulative energy demand (CED)**		
	CED, fossil	MJ-eq	(Frischknecht et al. 2004)
	CED, nuclear	MJ-eq	(Frischknecht et al. 2004)
Mid-point indicators	**CML characterisation**		
	acidification potential	kg SO_2-Eq	(Guinée et al. 2001a)
	eutrophication potential	kg PO_4-Eq	(Guinée et al. 2001a)
	freshwater aquatic ecotoxicity	kg 1,4-DCB-Eq	(Guinée et al. 2001a)
	human toxicity	kg 1,4-DCB-Eq	(Guinée et al. 2001a)
	ionising radiation	DALYs	(Guinée et al. 2001a)
	land use	m^2a	(Guinée et al. 2001a)
	terrestrial ecotoxicity	kg 1,4-DCB-Eq	(Guinée et al. 2001a)
	climate change (100a)	kg CO_2-Eq	(IPCC 2001)
End-point indicators	**Eco-indicator 99 (H,A)**		
	ecosystem quality	points	(Goedkoop & Spriensma 2000)
	human health	points	(Goedkoop & Spriensma 2000)
	mineral resources	points	(Goedkoop & Spriensma 2000)
	total	points	(Goedkoop & Spriensma 2000)

2 Results

2.1 Economic sectors chosen

This section includes the discussion of the results of the analysis of about 700 product and service datasets. The database content is structured into various economic sectors. Within the economic sectors chosen for the analysis, a selection of suitable datasets is performed. The selected datasets represent products and services that are usually an input to classical (consumer) product life cycle assessments: electricity, construction materials and metals, agricultural products and processes, as well as transport and waste management services. **Table 2** (see overleaf) shows the list of economic sectors and the number of datasets considered.

The results are shown in percentages as described in the previous section. The numbers in Table 2 show the median and, in brackets, the 10% and 90% percentile.

2.2 Electricity products

2.2.1 Non-renewable electricity supply systems

The analysis of non-renewable electricity systems covers country-specific electricity produced by hard coal, lignite, oil, natural gas and nuclear power plants as well as combined heat and power (CHP) production with natural gas and diesel cogeneration units.

In case of hard coal systems, contributions from capital goods dominate the cumulative results for the two indicators 'mineral resources' and 'land use' with mean values of 94% and 85% for all hard coal electricity datasets. These very high shares mainly originate in metal requirements and land use for the power plants, transport infrastructure and coal mines. The relatively high country-specific deviations for land use are due to different shares of coal from underground vs. open pit mines. The impact categories 'freshwater aquatic ecotoxicity', 'human toxicity', 'ionising radiation', 'CED, nuclear' and 'ecosystem quality' show relatively big country-specific deviations in the contributions from capital goods to cumulative results with shares up to about 40%. In case of aquatic ecotoxicity, this depends on the assumptions taken for the share of coal ash recycling: low recycling rate means that the disposal dominates the results and contribution from capital goods is reduced. This fact is also true for human toxicity, but also direct power plant emissions play a role – clean power plant technologies increase the share of contribution from capital goods, also for ecosystem quality. Ionising radiation and nuclear CED show similar country-specific patterns, which follow from the different origins of coal: in case of trans-ocean shipping more nuclear electricity is used for the infrastructure of the harbour than for the rail infrastructure. The importance of capital goods for the other analysed indicators is small.

Due to the lack of complex infrastructure for lignite mining and transport – power plants are usually operated mine-mouth – contributions of capital goods to cumulative results of the lignite chain are in general small with little country-specific variation, except of the indicators 'mineral resources' and 'land use' with mean shares of around 99% and 40%, respectively. The surface occupied by lignite extraction is allocated to the operation of the mine, therefore the share of capital goods is smaller than for hard coal. The relatively small importance of capital goods in the lignite chains is also reflected by the small mean contribution to the total Eco-indicator 99 (H,A) of 0.9% for all lignite electricity datasets.

Energy systems using oil normally show a comparably small contribution of capital goods. Most of the indicators show a capital goods' share of less than 10%. Exceptions are land use, the ionising radiation, CED nuclear, freshwater aquatic ecotoxicity and the Eco-indicator 99 (H,A), ecosystem quality.

For electricity from natural gas power plants, the relative contributions of capital goods to the indicators 'ecosystem quality', 'ionising radiation' and 'CED, nuclear' depend strongly on the country. The share of capital goods within these categories is high if the natural gas supply of the country depends heavily on long-distance gas transport (due to long-distance gas pipelines or infrastructure for liquefied natural gas production and transport). For example, the contribution of capital goods to 'CED, nuclear' (related to electricity needs, e.g. for

Table 2: Results of the analysis of selected ecoinvent datasets v1.2. The values show the percentage contribution of capital goods [median (10% percentile-90% percentile)] classification of contribution: white: minor (less than 10%); grey: substantial (between 10 and 90%); black: major (more than 90%); #: number of datasets considered; GLO: LCIA method with a global scope; RER: LCIA method with a European scope

	Unit	#	CML 2001	CML 2001	CML 2001	CML 2001	CML 2001	CML 2001	CML 2001
			Acidification potential	Eutrophication potential	Freshwater aquatic ecotoxicity	Human toxicity	Ionising radiation	Land use	Terrestrial ecotoxicity
			Generic	Generic	FAETP 500a	HTP 500a	ionising radiation	competition	TAETP 500a
			GLO	GLO	GLO	GLO	GLO	GLO	GLO
			kg SO_2-Eq	kg PO_4-Eq	kg 1,4-DCB–Eq	kg 1,4-DCB–Eq	DALYs	m^2a	kg 1,4-DCB–Eq
Electricity									
Hard coal	kWh	13	2.5 (0.9–5.0)	6.4 (2.7–8.4)	16.5 (2.4–25.4)	10.4 (6.6–18.1)	19.6 (10.5–41.7)	85.1 (71.4–89.0)	6.4 (4.6–12.4)
Lignite	kWh	14	0.1 (0.1–1.0)	0.8 (0.6–1.5)	0.5 (0.4–1.4)	7.1 (3.3–13.1)	5.1 (4.4–6.8)	39.7 (39.0–41.8)	2.2 (1.3–3.8)
Oil	kWh	23	1.9 (1.1–4.7)	4.8 (3.1–7.1)	17.3 (10.2–22.6)	4.1 (1.8–8.4)	43.1 (43.1–43.1)	96.6 (96.6–96.7)	4.6 (1.3–11.1)
Natural gas, average power plants	kWh	11	5.8 (4.7–9.6)	7.5 (6.4–9.1)	82.8 (71.4–87.2)	6.2 (5.1–7.6)	74.9 (54.1–89.6)	97.9 (94.2–98.8)	71.1 (64.5–73.8)
Natural gas, combined cycle plant, best technology	kWh	1	8.6 (8.6–8.6)	12.0 (12.0–12.0)	86.3 (86.3–86.3)	13.4 (13.4–13.4)	75.7 (75.7–75.7)	97.8 (97.8–97.8)	73.3 (73.3–73.3)
Cogeneration, natural gas, exergy	kWh	8	7.1 (5.8–18.6)	7.7 (6.5–17.3)	98.1 (97.7–98.4)	81.3 (77.6–91.0)	78.6 (75.4–80.0)	99.2 (98.7–99.2)	84.0 (82.7–84.7)
Cogeneration, diesel, exergy	kWh	1	7.5 (7.5–7.5)	8.0 (8.0–8.0)	53.4 (53.4–53.4)	33.6 (33.6–33.6)	41.9 (41.9–41.9)	97.9 (97.9–97.9)	37.6 (37.6–37.6)
Nuclear	kWh	6	22.5 (15.6–30.5)	27.6 (25.1–30.1)	35.9 (31.7–40.1)	71.5 (68.2–77.2)	0.1 (0.1–0.2)	97.7 (97.6–97.9)	52.8 (47.7–57.7)
Cogeneration, wood, exergy	kWh	4	4.4 (4.3–4.9)	1.6 (1.6–1.7)	40.7 (39.0–42.4)	9.0 (8.0–10.2)	20.0 (19.1–21.0)	1.2 (1.1–1.3)	11.3 (10.5–12.1)
Wind	kWh	6	99.4 (99.4–99.6)	99.2 (99.2–99.5)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	99.6 (99.6–99.8)	100.0 (100.0–100.0)	99.9 (99.9–100.0)
Photovoltaic	kWh	13	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)
Hydro electric power	kWh	32	99.6 (99.6–99.7)	99.6 (99.6–99.6)	100.0 (99.9–100.0)	100.0 99.9–100.0)	99.8 (99.7–99.8)	100.0 (100.0–100.0)	99.9 (99.9–99.9)
Electricity supply mix (low voltage)	kWh	26	4.2 (1.1–21.6)	6.9 (3.0–20.9)	23.7 (2.2–58.0)	62.6 (38.9–86.9)	1.3 (0.4–15.8)	76.8 (49.1–88.4)	42.8 (17.6–80.8)
Materials									
Construction Materials	kg	59	5.3 (2.3–17.3)	6.3 (2.6–17.2)	56.3 (24.2–78.5)	29.7 (11.0–54.0)	5.8 (2.5–20.3)	44.0 (3.9–91.7)	33.0 (5.7–66.8)
Glass	kg	4	8.2 (3.0–19.2)	5.9 (4.5–18.3)	48.3 (32.6–49.6)	54.0 (50.9–60.6)	13.2 (12.6–17.5)	66.6 (48.7–89.7)	57.0 (42.6–73.3)
Insulation Materials	kg	10	6.5 (4.0–11.6)	7.2 (5.1–10.1)	35.8 (24.2–40.5)	23.8 (20.4–53.4)	6.8 (1.3–28.2)	62.6 (2.2–86.3)	22.1 (11.1–42.1)
Mortar and Plaster	kg	10	5.4 (3.0–10.2)	6.2 (3.3–11.8)	34.6 (31.5–51.1)	27.4 (19.8–50.1)	3.1 (2.5–10.9)	14.6 (1.9–74.8)	19.1 (7.2–44.4)
Paints	kg	10	9.0 (6.8–10.8)	6.4 (3.0–9.9)	19.6 (14.3–65.9)	58.0 (10.5–67.4)	14.3 (10.2–26.2)	95.0 (12.6–98.6)	15.3 (8.3–23.5)
Wooden construction materials	m^3	46	10.0 (7.1–41.0)	9.0 (4.6–31.8)	60.7 (27.3–93.2)	31.1 (8.9–87.2)	10.8 (6.3–83.6)	0.1 (0.0–2.7)	55.5 (11.4–84.0)
Metals extraction	kg	73	3.2 (0.1–6.7)	6.6 (2.6–10.3)	2.7 (0.4–34.2)	5.0 (0.2–24.8)	3.7 (1.6–9.0)	51.9 (14.4–85.1)	9.7 (0.6–27.5)
Metals processing	kg	23	4.0 (1.7–5.7)	5.7 (3.3–11.5)	4.3 (1.2–25.2)	4.0 (0.9–32.0)	3.3 (1.0–5.1)	60.4 (45.6–84.3)	8.0 (0.9–19.7)
Agricultural products									
Agricultural products (plant production CH)	kg	40	3.7 (1.6–5.7)	0.5 (0.3–0.9)	40.8 (15.3–88.8)	51.5 (22.8–62.5)	55.4 (19.1–74.3)	1.0 (0.7–2)	1.4 (–1.8–6.7)
Agricultural products integrated (plant production CH)	kg	26	3.9 (3–5.9)	0.5 (0.3–0.9)	40.5 (4.3–89.4)	37.9 (22.6–62.3)	46.0 (25.2–68.3)	1.1 (0.7–1.9)	1.4 (–8.9–7.2)
Agricultural products organic (plant production CH)	kg	14	1.9 (1.3–4.4)	0.4 (0.3–0.6)	51.1 (26.5–71.4)	53.9 (47.6–62.4)	56.3 (18.4–75.1)	0.8 (0.6–1.8)	1.3 (0.1–5.2)
Seed production	kg	22	6.0 (2.0–8.5)	0.8 (0.4–1.6)	43.4 (2.1–72)	53.0 (29.1–58.4)	28.0 (13.8–38.3)	1.2 (0.7–2.7)	3.1 (0.2–8.8)
Feedstuff production	kg	10	4.4 (1.7–7.9)	0.5 (0.3–0.8)	42.3 (29.9–70.9)	53.2 (27.7–57)	31 (5–34.9)	1.0 (0.9–1.3)	3.6 (2–10.1)
Transport services									
Passenger Transport	pkm	12	25.7 (4.2–82.0)	19.7 (3.9–92.4)	88.0 (46.3–94.7)	75.1 (2.6–96.0)	25.1 (6.1–93.2)	97.8 (55.4–99.8)	73.1 (37.0–95.1)
Freight transport	tkm	19	14.1 (3.8–35.3)	11.3 (3.5–28.3)	85.0 (47.6–97.0)	50.5 (3.0–80.6)	88.2 (17.2–94.7)	99.7 (64.1–99.9)	72.5 (37.3–90.1)
Waste management services									
Municipal incineration	kg	44	6.6 (3.4–17.9)	5.3 (1.6–13)	0.3 (0–11.5)	11.3 (1.2–27)	25.1 (7.2–85.5)	74.4 (47.6–84.5)	22.4 (9–71.3)
Sanitary landfill	kg	28	45.2 (21.5–56.2)	20.5 (0.9–51.7)	0.1 (0–3.3)	18.0 (1.9–51.4)	41.9 (10.3–51.9)	55.7 (55.6–56.3)	41.2 (10.1–83.3)
Wastewater treatment	m^3	23	71.6 (20.4–97.3)	3.2 (0.2–96.6)	67.2 (3–89.5)	97.0 (42.5–99.5)	42.1 (5.5–66.4)	99.1 (95.2–99.8)	19.9 (1.4–98)
Residual material landfill	kg	45	65.2 (16.8–65.2)	2.1 (0.3–62.8)	0.1 (0–95.4)	5.8 (1.4–55)	91.3 (11.1–91.3)	58.5 (58.5–65.5)	89.3 (14.4–94.6)
Hazardous waste incineration	kg	10	7.8 (7.3–10.6)	9.2 (1.2–11)	7.4 (0.8–19.8)	34.3 (27.2–52.2)	24.7 (8.6–27.4)	88.8 (79.9–95)	32.6 (12.4–39.8)
Building demolition	kg	51	16.3 (4–45.7)	13.9 (3.7–43.4)	20.7 (0.1–91.7)	27.4 (5.2–48.3)	35.7 (10.4–91.4)	58.0 (55.1–90.9)	74.5 (13.9–87.7)

Table 2 (*cont'd*): Results of the analysis of selected ecoinvent datasets v1.2. The values show the percentage contribution of capital goods [median (10% percentile-90% percentile)] classification of contribution: white: minor (less than 10%); grey: substantial (between 10 and 90%); black: major (more than 90%); #: number of datasets considered; GLO: LCIA method with a global scope; RER: LCIA method with a European scope

	Unit	#	Cumulative energy demand	Cumulative energy demand	IPCC 2001	Eco-indicator 99, (H,A)	Eco-indicator 99, (H,A)	Eco-indicator 99, (H,A)	Eco-indicator 99, (H,A)
			Fossil	Nuclear	Climate change	Ecosystem quality	Human health	Resources	Total
			Non-renewable energy resources, fossil	Non-renewable energy resources, nuclear	GWP 100a	Total	Total	Mineral extraction	Total
			GLO	GLO	GLO	RER	RER	RER	RER
			MJ-Eq	MJ-Eq	kg CO_2-Eq	points	points	points	points
Electricity									
Hard coal	kWh	13	1.2 (0.8–1.8)	19.6 (10.5–41.9)	1.0 (0.6–1.5)	19.8 (11.5–30.3)	3.2 (1.2–4.6)	94.2 (91.5–98.9)	4.7 (2.8–7.2)
Lignite	kWh	14	0.3 (0.3–0.4)	5.1 (4.5–6.8)	0.2 (0.2–0.2)	1.9 (1.2–5.6)	0.4 (0.2–0.8)	99.6 (98.9–99.7)	0.7 (0.4–1.5)
Oil	kWh	23	2.2 (2.2–2.2)	43.1 (43.1–43.1)	2.2 (2.1–2.2)	18.1 (10.5–32.9)	3.9 (2.5–7.1)	99.1 (99.1–99.1)	3.4 (2.8–4.3)
Natural gas, average power plants	kWh	11	0.8 (0.6–1.0)	74.7 (53.1–89.2)	0.9 (0.7–1.1)	38.3 (28.6–45.9)	5.8 (4.8–6.8)	99.9 (99.8–99.9)	1.8 (1.3–2.2)
Natural gas, combined cycle plant, best technology	kWh	1	0.9 (0.9–0.9)	75.5 (75.5–75.5)	1.1 (1.1–1.1)	50.7 (50.7–50.7)	7.3 (7.3–7.3)	99.9 (99.9–99.9)	2.1 (2.1–2.1)
Cogeneration, natural gas, exergy	kWh	8	1.4 (1.2–1.6)	78.8 (75.8–80.1)	1.6 (1.3–1.7)	37.5 (33.9–59.6)	7.6 (6.5–10.9)	99.9 (99.9–100.0)	2.7 (2.3–3.1)
Cogeneration, diesel, exergy	kWh	1	2.6 (2.6–2.6)	42.1 (42.1–42.1)	2.5 (2.5–2.5)	48.2 (48.2–48.2)	8.8 (8.8–8.8)	97.6 (97.6–97.6)	4.8 (4.8–4.8)
Nuclear	kWh	6	31.8 (23.3–37.7)	0.1 (0.1–0.2)	33.1 (22.8–40.6)	73.3 (70.5–77.2)	12.7 (10.6–13.0)	78.8 (77.1–83.9)	24.6 (21.2–25.3)
Cogeneration, wood, exergy	kWh	4	30.5 (27.3–33.9)	20.3 (19.3–21.3)	15.4 (8.9–23.8)	4.7 (4.4–5.2)	4.2 (1.8–6.1)	99.1 (99.0–99.2)	6.8 (4.0–9.4)
Wind	kWh	6	97.7 (97.6–98.5)	99.7 (99.6–99.8)	98.9 (98.8–99.3)	100.0 (100.0–100.0)	99.7 (99.7–99.8)	100.0 (100.0–100.0)	99.3 (99.1–99.5)
Photovoltaic	kWh	13	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)	100.0 (100.0–100.0)
Hydro electric power	kWh	32	98.4 (98.4–98.6)	99.8 (99.7–99.8)	99.4 (94.2–99.6)	35.3 (27.8–93.8)	99.9 (99.4–99.9)	100.0 (100.0–100.0)	89.4 (87.0–98.8)
Electricity supply mix (low voltage)	kWh	26	2.1 (1.0–7.9)	1.4 (0.5–17.1)	1.9 (0.9–6.8)	48.3 (30.7–80.3)	7.4 (2.2–25.9)	99.5 (99.0–100.0)	10.4 (5.0–37.5)
Materials									
Construction Materials	kg	59	4.6 (1.6–12.7)	6.0 (2.6–20.4)	4.0 (0.7–7.7)	26.1 (–0.3–48.7)	5.9 (0.9–18.8)	90.9 (59.0–99.0)	6.8 (1.8–22.2)
Glass	kg	4	6.0 (4.3–9.5)	12.8 (12.5–17.5)	7.4 (6.1–10.9)	41.0 (9.8–71.2)	12.9 (6.6–20.2)	89.7 (48.2–97.5)	15.9 (7.4–22.4)
Insulation Materials	kg	10	4.6 (2.3–6.1)	6.1 (1.3–28.5)	5.7 (2.8–7.8)	34.2 (4.1–45.5)	9.0 (4.0–15.1)	83.0 (48.1–92.9)	6.5 (5.1–9.6)
Mortar and Plaster	kg	10	4.2 (2.8–6.9)	3.2 (2.5–10.8)	2.3 (0.8–7.2)	17.6 (12.5–50.1)	5.5 (2.4–15.4)	88.5 (72.0–98.7)	6.0 (2.9–9.7)
Paints	kg	10	4.9 (3.0–5.7)	14.1 (10.2–26.5)	8.0 (5.1–9.2)	47.0 (7.9–58.1)	13.8 (10.0–16.8)	99.1 (93.0–99.4)	8.3 (5.2–11.5)
Wooden construction materials	m^3	46	13.2 (4.7–54.3)	10.9 (6.3–83.8)	11.3 (6.1–54.9)	1.1 (0.3–12.9)	12.7 (8.6–53.7)	96.1 (82.4–99.0)	4.2 (1.2–9.2)
Metals extraction	kg	73	4.8 (2.6–10.8)	3.6 (1.6–9.5)	4.3 (2.2–8.7)	7.4 (0.9–26.2)	2.4 (0.5–7.4)	2.0 (0.2–97.4)	3.0 (0.5–7.1)
Metals processing	kg	23	3.1 (2.0–5.2)	3.5 (1.0–5.1)	2.9 (1.8–4.5)	9.0 (0.9–38.2)	3.2 (2.3–8.6)	8.2 (1.0–97.4)	3.5 (1.8–6.5)
Agricultural products									
Agricultural products (plant production CH)	kg	40	19.4 (16–34.8)	51.0 (19.5–63.1)	8.1 (5.1–14.3)	0.5 (0.4–1)	4.2 (–18.1–13.1)	98.9 (98.1–99.9)	2.0 (1.2–4.8)
Agricultural products integrated (plant production CH)	kg	26	17.6 (16–31.9)	46.6 (25.7–66.8)	7.6 (5.2–13.3)	0.6 (0.4–1)	1.8 (–24.8–6.4)	98.8 (98.1–99.7)	2.0 (1.1–4.9)
Agricultural products organic (plant production CH)	kg	14	24.8 (19.2–38.3)	56.7 (18.7–60.7)	11.0 (4.7–14.4)	0.5 (0.3–0.9)	7.4 (–6.4–15.8)	99.9 (98.6–100)	2.4 (1.5–4.1)
Seed production	kg	22	20 (15.1–34.3)	28.5 (14.1–38.9)	8.3 (6.4–16.6)	0.5 (0.3–1.3)	7.2 (1.4–16)	99.6 (98.1–99.9)	2.3 (1.3–6.1)
Feedstuff production	kg	10	20.1 (11.8–23.3)	31.6 (5.2–35.5)	7.5 (6.1–11.7)	0.7 (0.5–0.8)	6.8 (4.9–9.1)	99.3 (98.7–99.9)	2.6 (2.1–2.7)
Transport services									
Passenger Transport	pkm	12	19.6 (2.5–81.9)	25.4 (5.7–93.0)	16.4 (2.7–78.8)	50.4 (27.8–97.2)	30.2 (6.4–58.4)	99.7 (98.8–100.0)	24.0 (4.6–72.7)
Freight transport	tkm	19	20.1 (2.6–46.0)	88.2 (17.1–94.6)	18.1 (2.8–47.7)	37.3 (23.4–73.4)	17.5 (5.6–37.9)	100.0 (99.0–100.0)	20.1 (4.8–42.3)
Waste management services									
Municipal incineration	kg	44	30.8 (12.6–54.2)	25.6 (7.3–86.7)	3.1 (0.2–42.1)	5.6 (0.1–27.7)	4.1 (0.8–12.8)	98.5 (97.2–99.6)	2.7 (0.7–14.5)
Sanitary landfill	kg	28	78.5 (73.4–79.3)	45.8 (11.9–55.7)	10.3 (1–55.3)	10.8 (2–44.6)	1.8 (0.3–14.1)	99.9 (98.8–100)	4.5 (1.1–30.5)
Wastewater treatment	m^3	23	92.7 (35.9–96.6)	45.4 (6–69.3)	67.4 (16.5–85.3)	70.2 (13.5–97.3)	51.8 (9.6–95.7)	99.9 (98.2–100)	62.4 (12.7–96.4)
Residual material landfill	kg	45	86.6 (33–86.6)	92.3 (12.1–92.3)	71.3 (5.3–71.3)	24.5 (0.9–76.8)	4.0 (0.3–63.8)	100.0 (80.9–100)	5.9 (0.6–35.4)
Hazardous waste incineration	kg	10	3.7 (2.5–9.2)	24.9 (8.7–27.6)	2.3 (1.1–3.1)	40.4 (15.6–57.4)	9.6 (5.7–10.0)	99.3 (98.1–99.8)	5.1 (4.8–9.1)
Building demolition	kg	51	49.2 (11.8–69.6)	38.1 (10.4–91.8)	28.2 (0.3–51.6)	30.5 (2.4–202.2)	9.8 (1.1–25.2)	99.9 (98.5–100)	13.9 (2.3–41.2)

steel production) varies between 45% and 91% for different countries. The length of the gas pipelines related to the natural gas supply implies also significant variations of country-specific absolute cumulative impacts 'mineral resources' and 'land use', but the variation does not show up in the relative shares because these impacts are almost completely related to capital goods. For example, for the Netherlands (with a high share of their own gas production), the gas supply infrastructure contributes about 67% and the power plants contribute 33% to 'mineral resources'; for Austria (which depends entirely on gas imports, 86% of which are from Russia), the corresponding figures are 84% and 16%. The cumulative 'CED, fossil' for natural gas electricity is strongly dominated by the combustion of gas in the power plant, followed by the combustion of gas for gas production and transport, i.e. the contribution of capital goods to this impact category is very small (about 1% or less).

For small CHP plants, the material use per kW of the plant decreases significantly with increasing capacity (Heck 2004). Therefore, roughly speaking, the smaller the CHP plant within one technology class, the more important is the infrastructure of the plant in terms of impacts per kWh. The material use for capital goods plays a significant role in the categories of 'ionising radiation' and 'CED, nuclear' because of the electricity requirements for material production. For the 1000-kW_e CHP plant, capital goods contribute about 75% to these impacts (with exergy allocation), for the small 50-kW_e CHP plant at the same location (Switzerland), the share increases to over 80%. The contributions of capital goods to 'CED fossil' and 'climate change' are generally small, amounting at about 2.5% for the diesel CHP and ranging below 2% for all investigated natural gas CHP systems (exergy allocation). The contribution of capital goods to cumulative environmental impacts depends also on the allocation scheme used to attribute CHP burdens to heat and electricity.

Since only comparatively minor amounts of classical pollutants are emitted during the operation of nuclear power plants, infrastructure and capital goods are an important part of nuclear chains with respect to most indicators. Contributions from capital goods dominate the cumulative results for the impact categories 'land use', 'mineral resources', 'ecosystem quality' and 'human toxicity' with mean shares of about 98%, 80%, 74% and 73% for the nuclear electricity datasets. The only two impact categories with negligible contributions from capital goods are 'ionising radiation' and 'CED, nuclear' due to the radioactive emissions along the uranium fuel chain and due to uranium fuel consumption. Since ionising radiation makes about 40%–45% of total Eco-indicator 99 points, capital goods contribute about 20%–25% to the total Eco-indicator 99 (H,A) score. All impact categories show relatively small country and technology-specific deviations.

2.2.2 Renewable electricity supply systems

The analysis of renewable electricity systems covers electricity produced by photovoltaic panels, wind turbines and hydro power plants as well as combined electricity and heat production with wood fuelled cogeneration plants. Pumped storage hydro-electric power is not analysed here, since it is an electricity storage system (kind of battery) rather than a renewable energy system and the results exclusively depend on the electricity mix used for pumping.

All environmental impacts of the photovoltaic electricity supply are caused by the necessary capital goods. Direct impacts due to the operation account for less than 1% of all indicators investigated.

The results for wind power show that capital goods are of very high importance. Environmental burdens during operation are negligible from an LCA perspective, since contributions of capital goods to cumulative results are about 98%–100% for all addressed impacts with only very small standard deviations for all onshore and offshore turbines assessed in this paper. Very small contributions from operation are related to consumption of lubricating oil.

Electricity from hydro power plants shows similar results with the exception of the impact category 'ecosystem quality' with considerable differences between reservoir and run-of-river plants reflected in the standard deviation of 27%. While contributions of capital goods to cumulative results are about 93%–99% for reservoir plants, they are below 30% for run-of-river plants. One reason for this difference is that run-of-river plants are assumed to occupy a larger area per kWh electricity during operation, the other reason is the higher net damage associated to the type of land assumed to be flooded by run-of-river plants compared to reservoir plants. With those two facts capital goods become the dominating contributor to ecosystem quality for reservoir plants, but not for run-of-river plants. Since the damage assessment of land use in the CML-method is different – occupation of water surface is not included in the land use indicator based on land competition – land use during operation of the plants is invisible in the results.

The results for wood cogeneration systems (exergy allocation) show a major contribution of capital goods to cumulative results in the indicator 'mineral resources' (about 99%). Capital goods are not important for indicators, which are dominated by the effects of air pollutants like particles and NO_x, since these are mainly emitted during wood combustion and in the upstream chain. In contrast to all other energy systems analysed in this paper, land use caused by capital goods is negligible, since large areas are required for forests. The only impact category with a high variation is climate change. The reasons are N_2O emissions from emission control systems, which increase the total greenhouse gas emissions and therefore reduce the importance of capital goods.

2.2.3 Electricity supply mix

The share of capital goods on the results of low voltage electricity supply mix datasets (supply to households) varies between different countries depending on the power sources. Thus, e.g. for total Eco-indicator 99 (H,A) points, the share ranges between 3% (different countries with a high share of lignite power plants) to 89% in Norway (high share of hydropower). For individual indicators, the variation in the share of capital goods is quite high. Capital goods are generally important with regard to human toxicity, land use, Eco-indicator 99 (H,A) ecosystem quality and mineral resources. Only for climate change and the fossil Cumulative Energy Demand, the share of capital goods on the total results is always less than 10%.

2.4 Materials

2.4.1 Mineral construction materials

The mineral construction materials which have been studied cover the categories 'construction materials', 'glass', 'insulation materials', 'mortar and plaster' and 'paints'. The category 'construction material' contains bricks, concrete products, covering products such as fibre cement and gypsum slabs and some 'others' such as asbestos, milled limestone and ceramics. The category 'glass' contains mainly flat glass products and the category 'insulation materials' mainly foam glass, glass wool, rock wool, polystyrene and urea formaldehyde foam slabs. The category 'mortar and plaster' mainly contains one type of acrylic filler, cobwork, some coatings and some types of plaster and mortars. The category 'paints' contains different alkyd paints and different resins.

For all studied material categories the share of capital goods is higher than 15% for the following indicators: freshwater aquatic ecotoxicity (FAETEP 500a), human toxicity (HTP 500a), terrestrial ecotoxicity (TAETP 500a), land use, and ecosystem quality and mineral resources of the Eco-indicator 99 method. This quite high contribution is mainly caused by the metals (mainly steel) used in the production of machines and in reinforced concrete used in multi-storey buildings. For most production processes huge areas are covered with buildings, resulting in the high share of capital goods in the indicator 'land use'. The highest contribution of capital goods is found within the indicator mineral resources (83 to 99%). This is due to the fact that most mineral resources (limestone, bentonite, vermiculite, etc.) used as basis for the production of the products analysed in this paper are resources with no characterisation nor impact factor. In contrast to the fact that the resources considered in the indicator 'mineral resources' are mainly the metal ores which form the basis of the metal products. These metal products play an important part in the used capital goods (reinforcing steel, machines). The variation in capital goods share for all indicators and product categories are rather high, except those that show a relatively small share, i.e. acidification potential, eutrophication potential, ionising radiation, CED fossil and nuclear, global warming potential, human health and Eco-indicator 99 total. Despite the high capital goods share for mineral resources and for ecosystem quality (17 to 50%) the contribution to the total Eco-indicator score is quite low (6 to 9%).

2.4.2 Wooden construction materials

The analysis of wooden construction materials covers 46 datasets of the production of wood (including the production of residual wood) and of wooden products such as sawed timber, particle boards, etc.

The contribution from capital goods to total impacts is generally moderate (around 10–30%). However, in the impact category mineral resources, the capital goods are responsible for 96% of the overall impact. Also the freshwater aquatic ecotoxicity score (FAETEP 500a) and the terrestrial ecotoxicity score (TAETP 500a) are dominated by the capital goods (61% and 56%, respectively). These high contributions are basically caused by the metals used in the capital goods. The indicators 'land use' and the 'ecosystem quality', on the other hand, are dominated by non-infrastructure contributions (100% and 99%, respectively). This is obviously due to the land use of natural forests during the cultivation of trees. The variations in capital goods shares are rather high for all impact categories except land use and mineral resources. Similar to mineral construction materials, the capital goods share to Eco-indicator 99 total scores is low (4%) despite the high contribution of capital goods to the indicator scores of 'mineral resources. This is due to the wooden construction materials' low contribution to the 'ecosystem quality' indicator scores.

2.4.3 Metals

The analysis of metals covers 96 datasets of metal production (73 datasets) and of metal processing and refinement (23 datasets). Country specific production data, data on primary and secondary material production and different production mixes are included while intermediate products such as metal ore after beneficiation or liquid metal, etc. are excluded.

The contribution from capital goods to total scores is generally low (<10%). The only exception is the indicator 'land use', where capital goods contribute 52% for metal extraction and 60% for metal processing to the total score. This is mainly caused by the land use of buildings. For the metal extraction, land use for buildings in the mine (including residential buildings for the workers) is on the same order of magnitude as the land use for the extraction site itself (for open pit mining). The dominance of capital goods regarding land use is also due to the fact that the land use in underground mining is negligible and thus not inventoried in the ecoinvent mining datasets. The contribution of capital goods to the indicator 'mineral resources' is 2%. For metal extraction datasets, this share varies between 0.2% and 97%. This is due to the fact that several metals such as magnesium, cobalt, platinum, palladium and rhodium resources do not have an impact factor (high share of capital goods) while others do (low share of capital goods). For metal processing, the contribution of capital goods to the 'mineral resources' indicator is 8%, varying between 1% and 97%. For most of the processing datasets the contribution is rather small, but for 5 datasets where 'chemical plant' or 'aluminium casting, plant' represents the infrastructure, the contribution is very high. Thus, the high amount of chromium steel (18/8) needed in the chemical plant and the huge amount of heavy machinery used in aluminium casting seem responsible for the high variation.

2.5 Agricultural products and processes

We consider 40 products from agricultural plant production, which are further subdivided into products coming from integrated production (IP) and organic farming. Furthermore, we consider also 22 datasets for seed and 10 datasets for feedstuffs. The main infrastructure and capital goods items used in agriculture are buildings (including equipment) and machinery. To discuss the relevance of capital goods in the life cycle assessment studies in agriculture, we need to consider first some specific characteristics of agricultural production. Agricultural production is highly seasonal, dependent on weather conditions and often not continuous at all. Some machinery, like sowing or harvest machines, can be used only during a few days or weeks per year. Many work processes can take place only during dry conditions (e.g. soil cultivation or fodder harvest), which further limits the utilisation rates of machines. The same is true for buildings and equipment: e.g. fodder or manure stores can only partly be used and stables are empty during grazing periods. On the other hand, field and farm emissions (e.g. ammonia, nitrate, methane, phosphorus, heavy metals and pesticides) dominate certain environmental impacts. Therefore the share of capital goods on total impacts differs from that of typical industrial processes.

Nemecek et al. (2005) analysed the correlations between environmental impacts of farming systems and assigned the impacts to three groups: (i) impacts related to the use of capital goods and fuels: CED, global warming potential and ozone formation, (ii) impact related to the losses of the nutrients nitrogen and phosphorus: eutrophication and acidification and (iii) impacts related to the emission of toxic substances (mainly pesticides and heavy metals): ecotoxicity and human toxicity. Two other impact categories which are highly relevant for agriculture (biodiversity and soil quality) are not served by the ecoinvent database (no inventory records available). The analysis of the importance of capital goods will follow the grouping above.

Capital goods contribute about 20% to cumulative fossil and about 50% to the cumulative nuclear energy demand. These values are higher than for most industrial processes for the reasons stated above. It is interesting to note that the share of capital goods is significantly higher for organic products than for those stemming from integrated production (IP). This is explained by the fact that machinery is used at about the same rate in both farming systems, but that IP uses an important quantity of energy for fertiliser production. The share of capital goods on the global warming potential is substantially lower, which is explained by the fact that not only CO_2 but also N_2O and CH_4 (direct field and farm emissions) contribute to this impact.

Eutrophication is dominated by the nitrogenous emissions NH_3, NO_3^- and P-emissions, NH_3 is the main cause of acidification as well. These impacts are closely related to the use of fertilisers and losses in the field. Therefore the share of capital goods is low for acidification and almost negligible for eutrophication.

In respect to ecotoxicity and human toxicity the results are highly heterogeneous and dependent on the choice of the indicator. Many emissions have a potentially toxic effect, but only a few of them dominate the respective impacts. Terrestrial ecotoxicity, for example, is dominated by pesticides used in agricultural production, and therefore capital goods contribute very little to this impact. For other toxicity categories, pollutants related to the use of capital goods play a significant role.

Land use is a very relevant impact category in agriculture. Agricultural land is not considered as a capital good in the ecoinvent database. Only 1% is related to the use of capital goods, which is in striking contrast to most industrial processes. Land use is also a determining impact in the Eco-indicator 99 method. This explains why the share of capital goods is very low for Eco-indicator 99 totals. An exception is the use of mineral resources, almost fully related to capital goods. However, we have to keep in mind that phosphorus and potassium – two relevant mineral resources for agriculture – are not accounted for by the indicator 'mineral resources'.

2.6 Transport services

The analysis of transport services includes 12 passenger transport services provided by airplane (long and short-haul), by railway (regional, intercity and high-speed trains), by coach, regional busses and tramways as well as by private car. It also includes 19 freight transport services provided by lorries (different payloads, different regions, and different operation modes), by ship (transoceanic as well as inland waterways), by railway and by airplane. The share of capital goods is in most cases very much dependent on the transport means and the impact category. In terms of 'mineral resources', all transport services are dominated by infrastructure and capital goods contributions (more than 99% in any case). In terms of 'land use', all transport services except airplanes show a share of capital goods above 95%. Airplane transports reveal a capital goods share of 50 to 65% (lower shares for short-haul flights). Airplane transports also show the lowest capital goods shares (between 2 and 5%) with regard to fossil CED, climate change, acidification, eutrophication, human toxicity and Eco-indicator 99 totals.

Toxicity-related impact category indicators show capital goods shares of 50% and more, in particular in railway and road-based transportation services. Within road-based transportation, capital goods are particularly important with regard to freshwater ecotoxicity, where the share does not fall below 80%. With regard to climate change, manufacturing of vehicles and road transportation infrastructures contribute between 15 and 19% with a median value of about 17%. Within one transportation mean and one indicator, the results are in most cases rather homogenous. One exception are van transportation services, where the substantially higher emission factors (PM10, nitrogen oxides) of the average European van as compared to the average Swiss van leads to a substantially lower capital goods share in the former transport service (47% as compared to 63%).

There is no systematic difference in capital goods share between freight and passenger transports. The shares are similar for one particular transport means and one particular impact category indicator. Hence, capital goods shares differ because the transport means and the impact category indicator results behave differently.

2.7 Waste treatment services

The ecoinvent database features inventories for the assessment of the end-of-life phase of various products and production wastes. Disposal technologies include waste incineration (municipal and hazardous), several types of landfill, municipal wastewater treatment, underground deposits in salt mines, and surface spreading (landfarming). Not only disposal of *average* waste is inventoried (e.g. average municipal solid waste), but also *individual waste fractions* (e.g. waste paper). The elemental composition of the waste is heeded in determining the direct impacts from the disposal process. Thus, burdens of a disposal process are not merely determined by applied technology, as commonly encountered in inventories of industrial processes, but depend heavily on the *composition of the waste fraction* under consideration.

The burden contribution from capital goods can be very small if the assessed waste fraction has a *high pollutant content*. In that case, the direct emissions (from incineration and/or landfilling) are important. On the other hand, the burden contribution from capital goods can become quite large if a waste fraction has a *low pollutant content*, even though the same disposal technology is assessed. Glass packaging, for example as a fraction of municipal solid waste, can enter a municipal waste incinerator, but will create only very minor waste-specific (i.e. composition-dependent) impacts. This is because glass packaging usually has very low pollutant content and thus leads to very minor direct emissions. The contribution from capital goods of the disposal of this waste fraction in a municipal waste incinerator is 37% of the total burden as measured by Eco-indicator 99 (H, A). On the other hand, the contribution from capital goods of the incineration of *durable plastics* in a municipal waste incinerator, for example, is only 1%. This is a reflection of a high pollutant content within the plastic material leading to comparatively large direct emissions.

Remarkable are the results for wastewater treatment, where capital goods *dominate* most impact category results. This is due to the considerable infrastructure necessary for collecting wastewater, i.e. sewer systems, and the usually very diluted pollutant content in domestic wastewater. In highly concentrated industrial wastewaters, infrastructure can become less important, but – with the current ecoinvent datasets – is never insignificant.

Higher content of pollutants in a waste usually also means that more expenditures for the *abatement* of the emissions of pollutants are necessary during the disposal of this waste. One example is the lime consumption for abatement of sulphur dioxide emissions, which is only allocated to sulphur-bearing waste fractions. This results in additional, indirect capital goods burdens. However, these additional capital goods burdens do not cause an increased contribution from infrastructure, since they are also accompanied by further indirect non-infrastructure burdens.

Similar tendencies of low contributions from capital goods burdens with increased pollutant content of the waste fractions can be observed for all types of disposal activities and most indicators. Thus, contributions from capital goods to total impacts usually vary over a considerable range for different waste fractions even for individual impact category indicators and a particular disposal technology. As already noted for other datasets, the impact categories for land use and mineral resource use are usually dominated by capital goods burdens.

2.8 Synthesis

The analysis of a broad variety of datasets based on life cycle impact assessment results using a broad variety of methods confirms the fact that capital goods cannot be excluded per se. Firstly, toxicity related environmental impacts such as fresh water ecotoxicity or human toxicity are generally sensitive to the exclusion of capital goods. Secondly, capital goods contributions are dominating the impacts of certain products like photovoltaic and wind electricity, no matter which indicator is chosen. Nuclear electricity, agricultural products and processes, and transport services often behave differently than the products of other sectors, i.e. show a distinctly different share in capital goods.

Some indicators analysed here show a rather similar behaviour across all sectors analysed. This is particularly true for 'mineral resources', and – to a lesser extent – for 'Eco-indicator 99 total', 'acidification' and 'climate change'. On the other hand, 'land use' and 'freshwater ecotoxicity' show the most contrasting behaviour with shares of capital goods' impacts between less than 1% and more than 98%.

3 Conclusions and Recommendations

The relatively scattered pattern of the result of the analysis shows that not one simple rule can be formulated. Of course, if the scope of environmental impacts to be considered in an LCA is narrowed substantially during the goal and scope definition, one might be in a position to better judge the effects of including capital goods into the product system at stake. **Table 3** shows a synthesis matrix in which the importance of capital goods is classified distinguishing between economic sectors and environmental impacts.

With regard to *climate change*, capital goods may be excluded when analysing fossil-fueled electricity, and metals. But capital goods must be included in assessments of non-fossil electricity, transport services and certain waste management services.

With regard to *toxicity* impacts, any LCA omitting capital goods must be classified incomplete except for metals LCAs. In most cases they contribute substantial parts to the cumulative impact assessment results. The same is true with regard to *mineral resources*.

The earlier assessments in energy analyses are often used to substantiate the neglection of capital goods. It is shown that capital goods of agricultural products, of wooden products and of transport and waste management services contribute substantially to the non-renewable *cumulative energy demand*. Hence, even energy analyses cannot neglect capital goods *a priori*.

It becomes obvious that the environmental impacts caused by capital goods are not only significant with respect to less frequently applied impact categories such as ecotoxicity or land use. Even with regard to climate change, standard processes such as transport services release a substantial share of greenhouse gases by building, operating and maintaining roads and cars. This comes to a surprise because transportation, in particular road transportation, is perceived to be particularly CO_2-intensive in its operation.

It seems rather impractical to include or exclude capital equipment dependent on the environmental impacts regarded. Except for metals, all products and services analysed in this paper show at least substantial contributions in three or more environmental impact categories. Thus, it seems sensible to include capital goods manufacture by default in any case. In a large number of cases, rough assumptions and educated guesses are sufficient. Capital goods datasets need not necessarily be complete but cover relevant aspects such as land use. A combination of datasets including and excluding capital goods manufacture does not harm in principle. If capital goods are included in the LCI of one product because they are considered to be relevant there, they need not *a priori* be included in the LCI of its competing product, if their capital goods contributions are negligible.

Table 3: Share of impacts caused by capital goods manufacture on cumulative totals and recommendation regarding their inclusion in LCA case studies; black: capital goods must be included; grey: solid proof must be provided to exclude capital goods; white: capital goods might be excluded without specifying the reasons

	Land use	Mineral resources	Non-renewable CED	Climate change	Acidification / eutrophication	Toxicity and ecotoxicity
Fossil energy	major	major	minor	minor	minor	minor [a]
Nuclear energy	major	substantial	minor	substantial	substantial	substantial
Biomass energy	minor	major	substantial	substantial	minor	substantial
Renewable energy, nec	major	major	major	major	major	major
Metals	substantial	minor	minor	minor	minor	minor
Mineral construction materials	substantial	major	minor	minor	minor	substantial
Wood products	minor	major	substantial	minor	minor	substantial
Agricultural products	minor	major	substantial	minor	minor	substantial [b]
Transport services	major	major	substantial	substantial	substantial	Substantial
Waste incineration	substantial	major	substantial	minor	minor	minor [c]
Landfilling	substantial	major	substantial	substantial	substantial	minor [c]
Wastewater treatment	major	major	major	major	substantial	substantial

[a] substantial with natural gas; [b] minor regarding terrestrial ecotoxicity; [c] substantial regarding terrestrial ecotoxicity; CED: Cumulative Energy Demand; nec: not else covered (hydro, wind, solar)

The rather scattered pattern of varying importance of capital goods shown in Table 3 leads us back to two additional criteria. The first one is suggested by Heijungs et al. (1992a, p. 28). They consider the costs of maintenance and depreciation an initial indicator of the relative importance of capital goods: If these costs are a substantial part of the product price, the environmental impacts of capital goods should not be excluded *a priori*. The second one is about environmental significance: It is suggested to use the information on actual environmental hot spots within the supply chain of capital goods manufacture as an indicator complementary to the financial one. This kind of information can be accessed via scientific journals, renowned newspapers; even news on television can give first hints to such potentially relevant environmental impacts.

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