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PULP AND PAPER

LCA of a newsprint paper machine: a case study of capital equipment

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Abstract
Purpose The environmental aspects of paper as a consumer good have been extensively studied. However, the paper machine has been mostly neglected in the literature. The purpose of this article is to present a LCA case study that explicitly focuses on the system of a newsprint paper machine and its environmental impacts and not on the system of the consumer good paper. The relevance of the paper machine as capital equipment is analyzed, and conclusions for the environmental improvement of paper machines are drawn based on identified hotspots. The article hereby answers the more general research questions of whether capital equipment has rightly been neglected in other studies regarding pulp and paper and which impact categories are important for analyzing the environmental burdens of a paper machine.
Methods The study has been executed in collaboration with Voith Paper, an original equipment manufacturer. Hence, in distinction to literature-based studies, primary data on the paper machine was available resulting in a high overall data quality. Based on the ISO 14040 (2006) and 14044 (2006) standards, this article pursues a cradle-to-grave approach for the paper machine. It assesses the environmental impacts in the impact categories defined by the ReCiPe impact assessment methodology. Different types of energy generation are examined in a scenario analysis with combined heat and power generation (CHP) as the baseline case. For interpretation, a normalization and a sectoral analysis are performed.
Results and discussion The normalized results indicate fossil resource depletion and global warming as the most important impact categories. Global warming impacts are highly dependent on the energy processes and result to 432.7 kg CO2e per production of 1 t of paper for CHP and to 701.7 kg CO2e for EU25 grid mix. The sectoral analysis shows that the machinery's operations/use phase is clearly dominating most impact categories due to its long lifetime. An exception is the metal depletion, for which the materials and manufacturing processes are most important.
Conclusions These findings prove that for most categories, the operations/use phase of the paper machine is the most important life cycle stage. In systems focusing on the consumer good paper, it is therefore sufficient to model the operation of the paper machine, whereas the manufacturing, transport, and end-of-life processes regarding the paper machine equipment can be neglected, unless metal depletion is important to the study.

Keywords Capital equipment · Case study · Machinery · Paper · Pulp and paper industry

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1 Introduction

1.1 Background

The environmental impacts caused by the pulp and paper industry have been in the focus of policy makers for decades (EPA 1990; Frühwald and Solberg 1995; Klement and Dyllick 2000; Umweltbundesamt 2000).

The resources used for paper making, wood and other comparable biomass, are per se regenerative. However, the processing in pulp and paper production uses large amounts of chemicals and energy. Many different types of paper exist ranging from printing and writing paper, tissue, different kinds of packaging papers, and boards to specialty papers. The different paper types allow for different grades of recycling, which significantly influence the quantity of used natural resources and forestry processes. In this context, the amount of necessary assumptions, the complex relationships, and the difference in questions make the environmental evaluation of paper systems difficult and can admittedly lead to contradictory results (Finnveden and Ekvall 1998; Umweltbundesamt 2000). Therefore, it seems reasonable to isolate single aspects like the paper machine and its operation in paper production in order to come to stronger conclusions for narrower questions.

More recent data shows that in terms of climate impact, the pulp and paper industry is responsible for 1.1 % of worldwide greenhouse gas (GHG) emissions (World Resources Institute 2009) and 2.3 % of the US GHG emissions (World Resources Institute 2008). In addition, the pulp and paper industry is subject to the emission trading system in the European Union since 2005 (EU 2012; Directive 2003/87/EC) resulting in a serious economic relevance of GHG emissions (Hübner 2007). For the fast growing Chinese paper industry, a recent study examines chances of participating in the global emission trading defined by the Kyoto protocol through clean development mechanisms (Liu et al. 2011). Consequently, environmental impacts of pulp and paper related processes are nowadays not only relevant for public bodies but of vital interest for the industry itself. The original equipment manufacturers (OEM) are being pushed for disclosing the environmental impact of their machinery and for improving their products by the paper producers facing these challenges. These aspects highlight the relevance of high-quality environmental assessments of the sector incorporating industry data.

The present paper, therefore, analyzes the environmental impact of a typical newsprint paper machine using the life cycle assessment (LCA) approach. In cooperation with Voith Paper, one of the leading OEMs for the paper industry, this article explicitly examines the product system of the paper machine (and not the one of paper). The opportunity to include primary industry data provided by Voith Paper leads to a high overall data quality in the study. The contribution of this article is given by:

- Providing a state-of-the-art of selected studies applying LCA to pulp and paper
- Transparently calculating the environmental impact directly attributable to the life cycle of a newsprint paper machine
- Analyzing the environmental importance of capital equipment in the paper industry
- Identifying hotspots in the life cycle that provide the biggest leverage for environmental improvement of paper machines
- Drawing conclusions for OEMs and paper producers

1.2 State-of-the-art and research gap

Many articles have analyzed different aspects of the paper industry using the LCA methodology. Gaudreault et al. (2007) describe the general relevance of LCAs on paper by analyzing the types of studies and their organizational and regional origin. For printing and writing paper produced in Portugal, Lopes et al. (2003) and Dias et al. (2007) have found that the energy use during paper production is the biggest contributor to air emissions. Dias and Arroja (2012) examine different carbon footprinting standards. Another very comprehensive study on printing and writing paper has been published by the German Federal Environment Agency comparing different options of fiber resources and recycling (Umweltbundesamt 2000). Gaudreault et al. (2010) show the relevance of system boundary selection by varying energy sources and the share of recycled fibers for an integrated newsprint mill. Quite a number of studies focused more narrowly on certain aspects of the paper system, for instance, the end of life options of paper recycling compared to wastepaper incineration. In a literature-based work, Ekvall (1999) identified energy processes and forestry options as key issues when analyzing recycled paper against virgin fibers and waste incineration. In a meta-analysis of seven studies from Scandinavia, Finnveden and Ekvall (1998) observe a general advantage of paper recycling over incineration in terms of total energy use and use of biomass resources, although with varying results in the impact assessment categories depending on the energy sources. Ross et al. (2003) also indicated a general advantage of recycling for containerboard and focused on policy development. Furthermore, print products have been analyzed using LCA by Pihkola et al. (2010) and Krokowski et al. (1998). For testliner, Iosip et al. (2012) describe the importance of collection and screening of wastepaper by showing a significant influence of secondary fiber quality and contamination on the energy consumption of various processes in the paper system. Skals et al. (2008) and Zhi Fu et al. (2005) focus on the use of enzymes as a substitute for chemicals in pulp processing. An LCA on forestry processes and management in Finland has been performed by Seppälä et al. (1998). Mourad et al. (2012) investigate the developments of environmental impacts of liquid packaging boards in an industrial case study. Figure 1 summarizes the state-of-the-art and locates the studies according to their focus in the paper life cycle. Overlapping processes between studies in the literature and the present paper are indicated.

All of the above cited work puts the system of paper as a consumer good in the focus of attention. Capital equipment is neglected, only accounting for its operation, without further disclosure of the reasons (e.g., Lopes et al. 2003; Dias et al. 2007; Dias and Arroja 2012). In other studies, it is not mentioned at all. The only exception is an ecoinvent dataset on paper machines which consists of “a rough estimation based on few information”[1].

[1] Dataset: paper machine, at paper mill #5835 (Ecoinvent 2012). The dataset has been created in 2003 and does not cover the operation of the paper machine. Roads and buildings are included. In terms of metals, only steel and chromium steel are considered in the dataset. Information on the overall weight and the amount of chromium steel actually originated from Voith Paper, while all other data were estimated. The data quality of the ecoinvent set has to be regarded as inferior in comparison to the more comprehensive and up-to-date primary data from Voith Paper used in the present study.

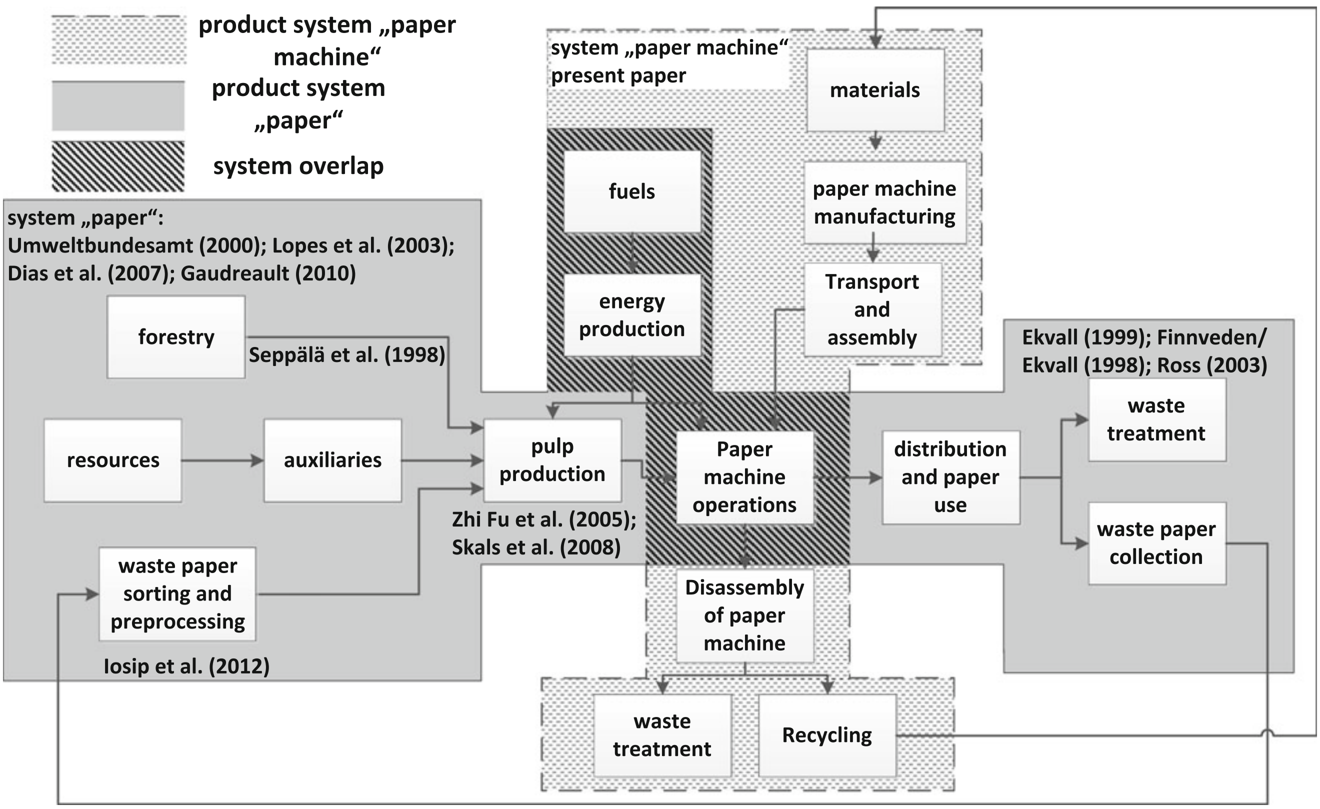

Fig. 1 State-of-the-art and research gap

To my knowledge, the paper machine has not been considered explicitly and extensively studied in any further publications, although Frischknecht et al. (2007) showed that capital goods might well be relevant in LCA studies. Also, Finkbeiner (2009) identified the treatment of capital equipment as an unfinished research field for carbon footprinting. The present article fills in to this gap by addressing the system of a paper machine and by answering the following research questions that are of importance beyond the case study:

- Which impact categories are most important for analyzing the environmental burdens of a paper machine or comparable equipment?
- Has capital equipment rightly been neglected in other studies regarding the pulp and paper industry?

2 Methods and materials

The product system under study represents a typical large size paper machine producing newsprint paper from 100 % recycled fibers in a stand-alone setup. An annual production of 360,000 t of paper under normal conditions and a machine lifetime of 40 years are assumed. The system models the life cycle of the paper machine from cradle-to-grave as it is of interest for OEMs and paper producers. It incorporates current best (competitively) available technologies built and operated in the European Union. The paper machine comprises all machinery parts from deinking process (DIP) equipment through wire, press, and dryer section all to the calender and roller. Necessary background equipment such as the steam and condensate system and hydraulics are also accounted for. Further finishing equipment such as slitter winders and packaging as well as the factory buildings and roads were excluded. A newsprint machine has been chosen for analysis for reasons of comparability. It represents the common technological basis of most large graphical paper machines. Therefore, the general conclusions derived in this article can be expected to be valid for other graphical paper machines and graphical paper grades as well, although quantitative results may vary. For tissue paper and board, the machinery is significantly different, and the content of this article might only roughly apply.

The case study presented here has been executed as a process-based LCA according to the methodology outlined by the ISO standards using the LCA software GaBi.[2] High-quality primary data provided by Voith Paper have been used for modeling manufacturing materials and the operating parameters. For all other processes, as for example materials acquisition and purchased energy, average process data have

[2] www.pe-international.com/

been used. The methodology is thereby consistent with an attributional life cycle assessment and meets the goal to quantify the environmental impacts of a typical product as described by Gaudreault et al. (2010).

Table 1 gives an overview on the system specifications and some important cumulative life cycle inventory data.

2.1 System definition and functional unit

A specific challenge within this work is the definition of the system, its boundary, and the functional unit. With the product under study being the paper machine, the system differs significantly from systems describing the consumer good paper where the paper machine is a capital good. Frischknecht et al. (2007, p. 2) stated that “the object of investigation in one study may well be the capital good in another one” (based on Guinée 2002), as it is the case here. To make the results robust and valuable to other LCA practitioners in pulp and paper, the system has to be clearly defined and distinguished from systems describing the paper life cycle.

The system as shown in Fig. 2 includes the manufacturing of the paper machine with relevant materials and waste treatment as well as the transport to the customer site. Obtained data revealed early on that the assembly and startup processes are negligible over the life cycle. Accordingly, assembly and startup have been excluded from the study. The operations/use phase including fabrics as the main consumable and the disposal and end-of-life processes complete the system. The fabrics as consumables have been modeled using an LCA module previously developed by Voith Paper.[3] The operations/use phase in the center of the system includes all relevant inputs necessary for running the machine, that is, energetic inputs and water (see Fig. 2). However, it does not include any fibers, fillers, auxiliary chemicals, or other in- or outputs for the paper production in the sense of material processing. For all life cycle stages, emissions to air, water, and soil have been considered.

This way, the results for the operation of the paper machine as defined here can equally be utilized as the use phase in the system “paper machine” as well as the production phase in the system “consumer good paper”. Considering the interconnection between the two systems, the work can be interpreted as a cradle-to-grave study of the paper machine. It could also be used as a model of the paper machine operation (including capital equipment) within the product system of paper as the consumer good.

In order to describe and define the paper machine system under study, an adequate functional unit can then be phrased as follows:

> Construction and average operation of a newsprint paper machine in the European Union for the production of 1 t of recycled paper at 360,000 t per year and a lifetime of 40 years.

[3] The module describes the global average mix of the fabrics produced by Voith Paper considering materials, production, transport, and disposal.

Table 1 System specifications and cumulative inventory data

System specifications		Unit
Production capacity	360,000	t/year
Lifetime	40	years
Width	~10	m
Overall weight	9,800	tons
Cumulative inventory data		
Consumption of		
Iron ore (56 % Fe)	1.2E+07	kg
Chromium ore (39 % Cr)	1.0E+07	kg
Copper ore (~1–2 % Cu)	1.4E+07	kg
Bauxite	1.7E+06	kg
Natural gas (for CHP)	2.7E+09	kg
Emission of		
NO_x to air (for CHP)	9.0E+06	kg
CO_2 to air (for CHP)	5.74E+09	kg
SO_2 to air (for CHP)	5.24E+06	kg
Phosphorus to fresh water	753	kg
Phosphorus to soil	13,520	kg

2.2 Data collection and modeling

2.2.1 Materials and manufacturing

For the manufacturing of the paper machine, primary data of Voith Paper has been used. The types and amounts of materials used in the different modules of the machine have been extracted from bills of materials or inquired from suppliers. The obtained data has then been validated using overall weights provided by the logistics department. Metals considered are steel, chromium steel, cast iron, copper, and aluminum. Further materials have been modeled as thermoplastics, elastomers, and isolation material (rock wool). Fossil fuels and electricity in manufacturing have been modeled as EU25 average.

Due to the complexity of a paper machine, the sheer amount of parts and the duration of manufacturing, the energy use, and manufacturing wastes could not be measured or inquired with a reasonable effort. Therefore, accessible site-specific input–output data on total energy consumption and waste in manufacturing from Voith Paper's facilities has been used. The measures of the sites have been scaled to the paper machine under study with an economic allocation based on

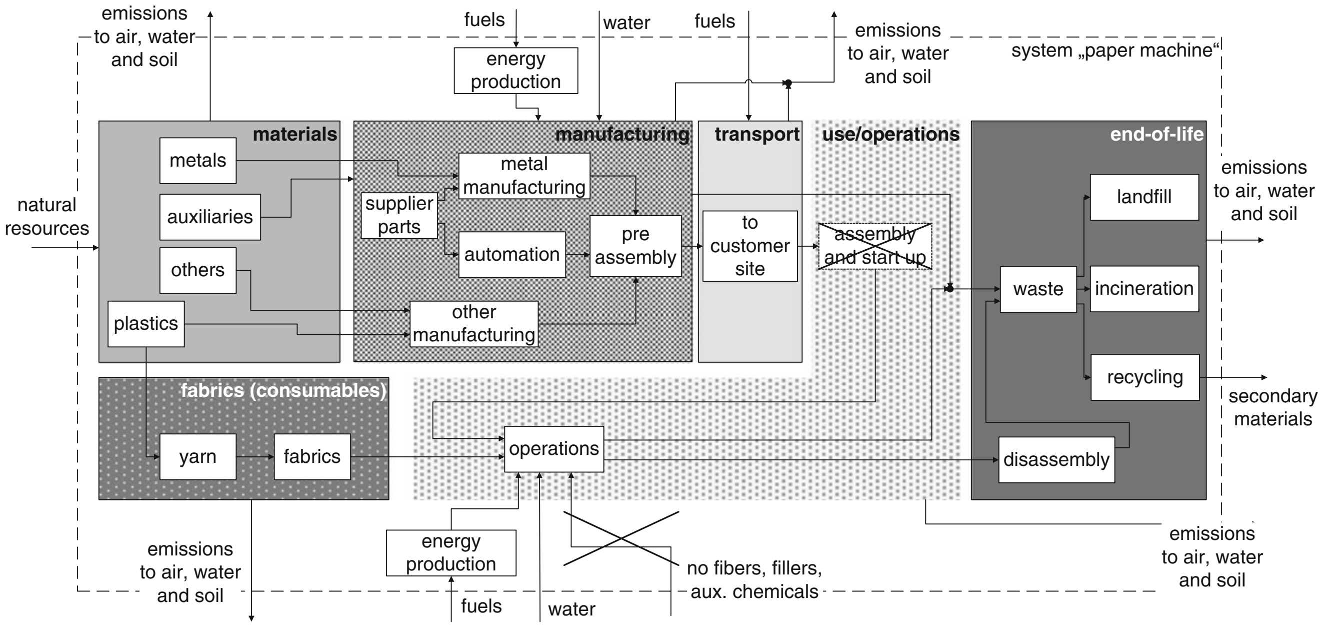

Fig. 2 Process map of the paper machine system

sales. The allocation factor has been calculated by dividing the sales volume realized by those parts related to the studied machine manufactured at a respective site by the total sales at that site.

Materials acquisition and preproduction has been modeled using average process descriptions from databases such as the ELCD and PlasticsEurope provided with the GaBi software (PlasticsEurope 2012; European Commission 2012).

For the transport of the machinery to the customer site, average distances from manufacturing facilities to a location in Central Europe have been estimated. Due to the size and weight of large-size equipment like paper machine modules, only road and ship transports have been considered.

2.2.2 Operations/use phase and energy

The operations/use phase is crucial for the overall environmental impacts due to the high energy consumption and the long lifetime of a paper machine. The operating parameters are therefore of high importance for the study. Firsthand data has been provided by the engineering of Voith Paper for the so called normal running load, which describes the power requirements at the average operating point under normal conditions, which the equipment has been designed for. The primary data has been checked against information given in the literature (e.g., European Commission 2001).

As stated above, the operation of the paper machine requires a large amount of energy. For the automation and controls, vacuum systems, hydraulics, and especially for powering the drives, electric energy is required. Additionally, there is a constant need for thermal energy in the form of steam. Especially for heating the cylinders in the dryer section, large amounts of thermal energy are required. The need for both energy forms, electric and thermal energy, makes cogeneration a preferred option for energy production in the paper industry. Therefore, the baseline case for energy generation in the studied system is a natural gas fueled combined heat and power plant (CHP). Since the absolute amount of thermal energy needed is higher than the amount of electricity, the CHP process is scaled to satisfy the thermal energy need. Due to the ratio of the coproducts, an excess of electric energy is produced, which can be fed into the public grid. In analogy to other LCA studies of the paper industry (Lopes et al. 2003; Dias and Arroja 2012) and suggestions for the allocation of energy cogeneration (e.g., Azapagic and Clift 1999), the avoided burdens approach is used to model the CHP. The excess energy then substitutes electricity from the EU 25 grid.

Employing a scenario analysis, the acquisition of electric energy from the public grid mixes of Germany and an EU25 average in connection with the on-site production of thermal energy via a gas fired boiler are analyzed (Table 2).

2.2.3 End of life and waste treatment

For the treatment of manufacturing wastes, the current best practices can be assumed. Due to the long lifetime, the end-of-life processes for dealing with the residues of the paper machine itself will take place in the distant future and are uncertain. Nevertheless, it can be assumed that the recycling and waste treatment processes in the future will eventually be more environmentally friendly than the best available technologies of today. By using today's technologies for modeling

Table 2 Cases for scenario analysis

Scenario cases	Energy production
Baseline: CHP	CHP, gas fueled
Scenario EU25	EU25 grid and gas boiler
Scenario GER	German grid and gas boiler

the machine disposal, a worst case is represented, presuming that no improvement in waste processes is achieved until the end of the system's lifetime. This is preferable to not modeling the machine disposal at all.

Additionally, in the present study, secondary materials obtained by recycling during end of life have not been credited for substituting primary materials. Some of the materials processes consider a certain amount of secondary raw materials as input. The steel dataset considers ~18 % secondary material input and the stainless steel dataset ~65 %. This way, the modeling reflects the recycled content method for those materials as proposed for long lasting systems with uncertainty regarding the end of life (GHG Protocol 2011). The datasets on copper, aluminum, and the other materials do not contain secondary material input and are treated as primary raw materials.

With the recycled content method, which does not credit primary material substitution, the modeling of end of life differs to the approach for the CHP process, where substitution was credited for excess electrical energy. Each approach seems suitable for the particular case and applies with respective suggestions in the literature. Both are different processes with different in- and outputs, such that the ISO standards allow for a differentiated modeling.

2.3 Impact assessment

The life cycle impact assessment has been realized according to the ReCiPe impact assessment method for midpoint indicators (Goedkoop et al. 2013; ReCiPe 2013). The considered impact categories are global warming, marine, and freshwater eutrophication, acidification, fossil and metal resource depletion, photochemical ozone creation, ozone depletion, as well as human toxicity, terrestrial, marine, and freshwater ecotoxicity, further water depletion, ionizing radiation, and particulate matter formation. Except for land use related categories, which have not been considered, all impact categories were calculated and analyzed. Data collection and data quality considerations, however, have been made focusing on the global warming category, as the relevance of GHG emissions for the paper industry was the motivation for carrying out this study.

Considering the cumulative inventory emission data from Table 1, NO_x is the main contributor in the impact categories of marine eutrophication and photochemical oxidant formation and is emitted mainly by the energy processes and the natural gas extraction, both of which are modeled based on secondary process data from PE International and ELCD datasets. SO_2 also mostly stems from natural gas extraction and energy processes and is crucial for terrestrial acidification and particulate matter formation. CO_2 of course is critical for climate change and is mostly emitted by the combustion of fossil fuels for energy generation. Phosphorus emissions to freshwater and to soil contribute significantly to the ecotoxicity impact categories and the freshwater eutrophication and are emitted to a large extent during natural gas extraction.

For the impact assessment, midpoint level indicators are calculated to describe the environmental impacts caused by the paper machine life cycle. An impact assessment based on endpoint indicators would involve a greater deal of uncertainty and value judgment within weighting (Bare et al. 2000; European Commission 2010). To avoid this as far as possible and to keep the study transparent, endpoint impact assessment has not been realized. In addition, this study seeks to transparently inform actors in the paper industry about the environmental impacts of the life cycle of a paper machine and make the results available for other LCA practitioners. Midpoint indicators seem to be the adequate way to reach this goal.

3 Results

Table 3 shows the results per functional unit for the examined impact categories for the baseline case of the production of thermal and electric energy by a gas fired CHP, as well as the two considered grid mix-based energy scenarios. The negative results for ozone depletion and ionizing radiation arise from the substitution of electricity from grid by excess electric energy from the CHP process.

To get a deeper understanding of the importance of the different categories and the influence of the energy scenarios, a normalization of the results has been done based on the ReCiPe normalization dataset for Europe (ReCiPe 2013). Expressed in person year equivalents, the normalization in Fig. 3 answers the first research question defined in Sect. 1.2 and gives an indication of the relative importance of the impact categories in dependence on the energy generation. The most relevant impact category for the paper machine product system is the fossil resource depletion followed by global warming. Terrestrial ecotoxicity and metal depletion are of lesser but nearly equal importance for all types of energy generation. Human toxicity, acidification, particulate matter formation, as well as photochemical ozone creation and ionizing radiation show a much larger dependency on the energy scenario. Throughout all impact categories except for freshwater eutrophication, the cogeneration of thermal energy

Table 3 Impact assessment results

		Result per functional unit		
Impact category	unit	CHP	GER	EU25
Climate change (GWP100)	(kg CO_{2e})	432.74	751.74	701.71
Fossil depletion (FDP)	(kg oil_e)	194.52	224.88	206.51
Freshwater ecotoxicity (FETP)	(kg 1,4-dB_e)	0.011	0.025	0.027
Freshwater eutrophication (FEP)	(kg P_e)	1.00E-03	9.62E-04	1.04E-03
Human toxicity (HTP)	(kg 1,4-DB_e)	8.369	18.694	21.799
Ionizing radiation (IRP)	(kg $U235_e$)	−14.487	116.163	131.198
Marine ecotoxicity (METP)	(kg 1,4-DB_e)	9.353E-03	0.041	0.059
Marine eutrophication (MEP)	(kg N_e)	0.024	0.032	0.041
Metal depletion (MDP)	(kg Fe_e)	9.655	9.773	9.756
Ozone depletion (ODP)	(kg CFC-11_e)	−1.20E-05	9.62E-05	1.08E-04
Particulate matter formation (PMFP)	(kg $PM10_e$)	0.068	0.266	0.694
Photochemical oxidant formation (POFP)	(kg NMVOC)	0.169	0.704	1.186
Terrestrial acidification (TAP100)	(kg SO_{2e})	0.364	0.873	2.625
Terrestrial ecotoxicity (TETP)	(kg 1,4-DB_e)	0.124	0.121	0.133
Water depletion (WDP)	(m3)	4.473	5.747	5.731

and electricity in a CHP proves environmentally superior compared to the grid mixes. The German grid mix is advantageous compared to the EU25 mix in all categories except for global warming, fossil depletion and water depletion.

The sectoral analysis in Fig. 4 shows the contribution to the different impact categories by life cycle stage for the energy scenarios and answers the second research question defined above. Apart from metal depletion and partially marine ecotoxicity, the contribution of the operations/use phase is

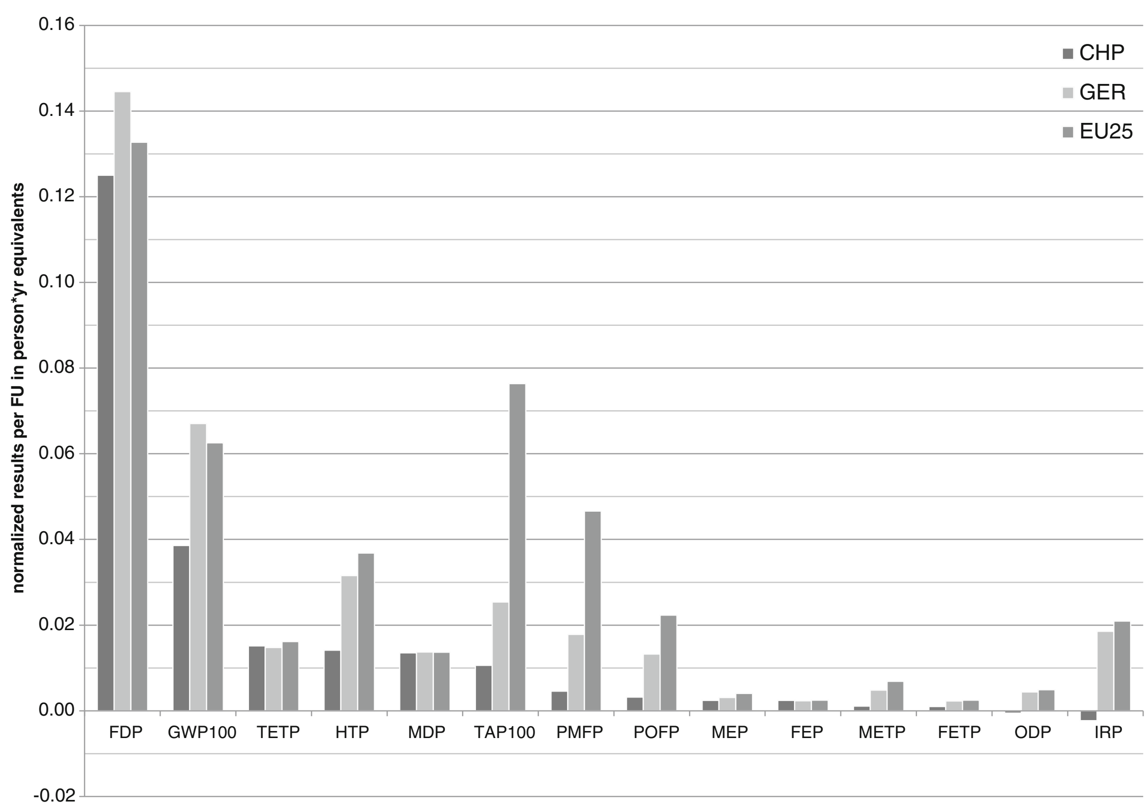

Fig. 3 Normalized results

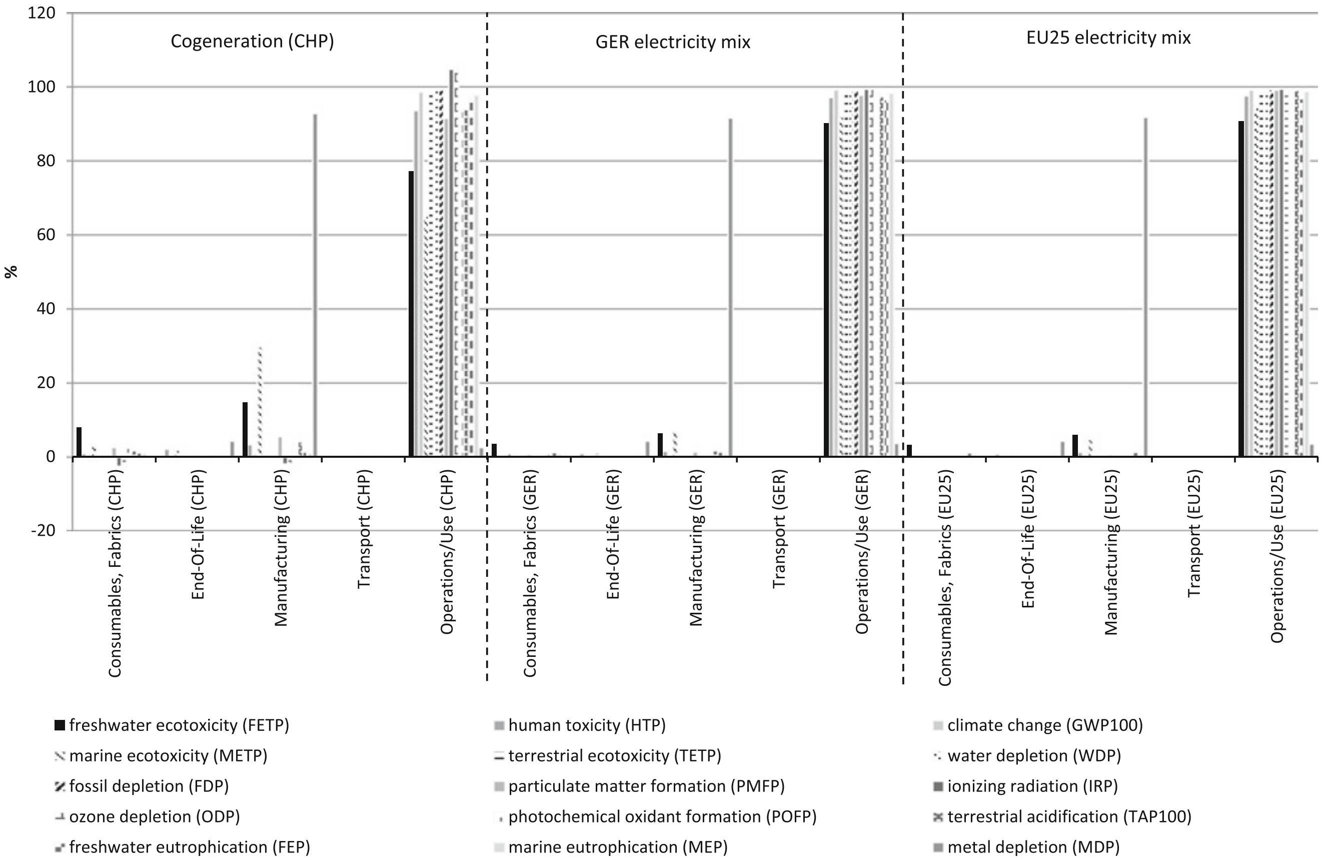

Fig. 4 Sectoral analysis

dominant for all other impact categories. In these other categories, close to 100 % of all impacts occur during the operations/use phase. This result is mostly determined by the paper machine's long lifetime of 40 years (see Sect. 2). While the operation of the machine with its need for large amounts of energy happens continuously over the 40 years, the other life cycle stages like manufacturing and materials, transport, and end of life occur only once. The accumulated energy input for the operation of the machine is extremely high compared to the other life cycle stages, resulting in a high contribution to the energy sensitive impact categories. The metal depletion and in part marine ecotoxicity are exceptions to this. Metal depletion is hardly affected by energy consumption and experiences the biggest contribution of more than 90 % of the impacts from manufacturing and materials regardless of the energy scenario. For the CHP case, manufacturing is relatively important for marine ecotoxicity and causes around 30 % of the impacts. Copper is the main contributor in manufacturing to marine ecotoxicity. Its specific impact per mass unit is 20 times higher than that of stainless steel and aluminum and about 80 times higher than that of cast iron. In the case of both of the grid mixes, the total impacts to marine ecotoxicity are significantly higher than with CHP, and only about 5 % of the impacts arise during manufacturing. The largest impact is caused by the energy processes during the operations/use phase.

Figure 5 compares the results of the global warming potential in kg CO_2 as well as the NO_x and SO_2 emissions of the energy scenarios to publicly available data for the operation of comparable paper machines (in Krokowski et al., only CO_2 results were available). This validation with data from the sources proves the results of the respective emissions to be in the correct order of magnitude. The GER scenario performs worse than the EU25 scenario for CO_2 due to the power generation technologies that contribute to the respective grid mix. Coal is a large contributor to the German grid mix, while in the whole EU25, hydropower from the Scandinavian and the Alpine countries result in a lower GHG emission. However, the German grid mix performs better than EU25 for NO_x and SO2. CHP results in the lowest global warming and SO_2 impact, while its NO_x emissions are slightly higher than with the GER mix. The CO_2 result of CHP is comparable to or lower than the values in the literature, which seems reasonable for the assessment of a state-of-the-art paper machine. NO_x emissions as calculated in this study are similar to the literature. SO_2 emissions are slightly higher than available data but still within a comparable magnitude.

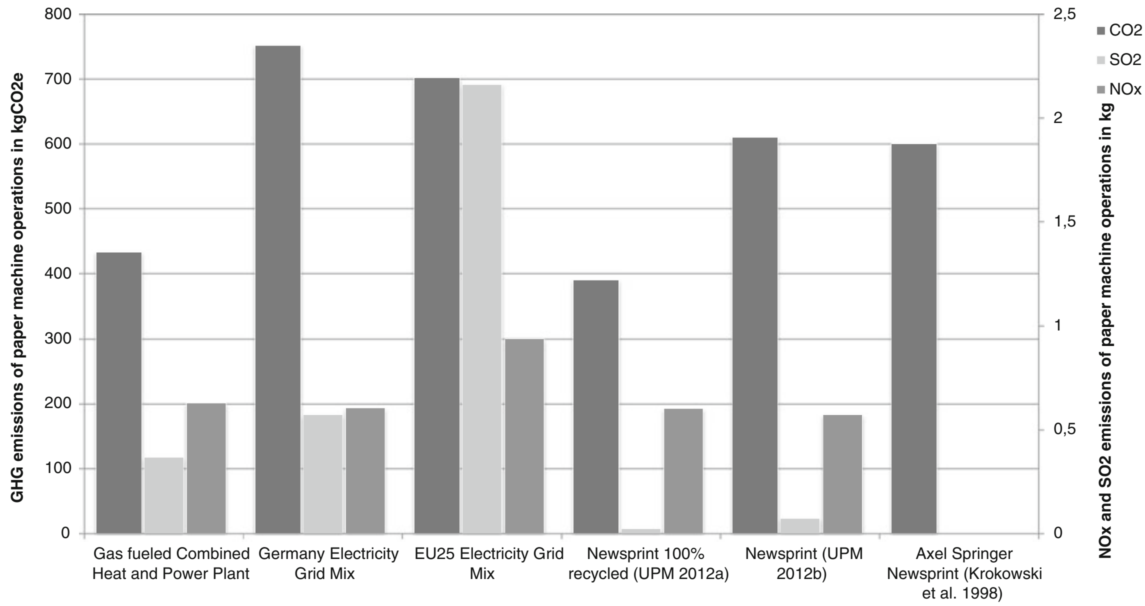

Fig. 5 Validation of GHG, NO_x, and SO_2 emissions

4 Discussion

The normalized results have shown that the depletion of fossil resources and global warming are of great significance. The importance of other categories like human toxicity or acidification varies greatly with the considered form of energy generation. The sectoral analysis has shown a huge dominance of the operations/use for most impact categories. Only for metal depletion, the manufacturing proved most important. For marine ecotoxicity, manufacturing can be of relative importance for the CHP case.

As discussed in the state of the art, the ecoinvent database contains a dataset on paper machines, which does not consider the operations of the machine. For comparison to the ecoinvent data, the results of the present study have to be modified to approximately comply in scope and functional unit. Therefore, the operations/use phase impacts have been subtracted from the overall cumulated results such that only

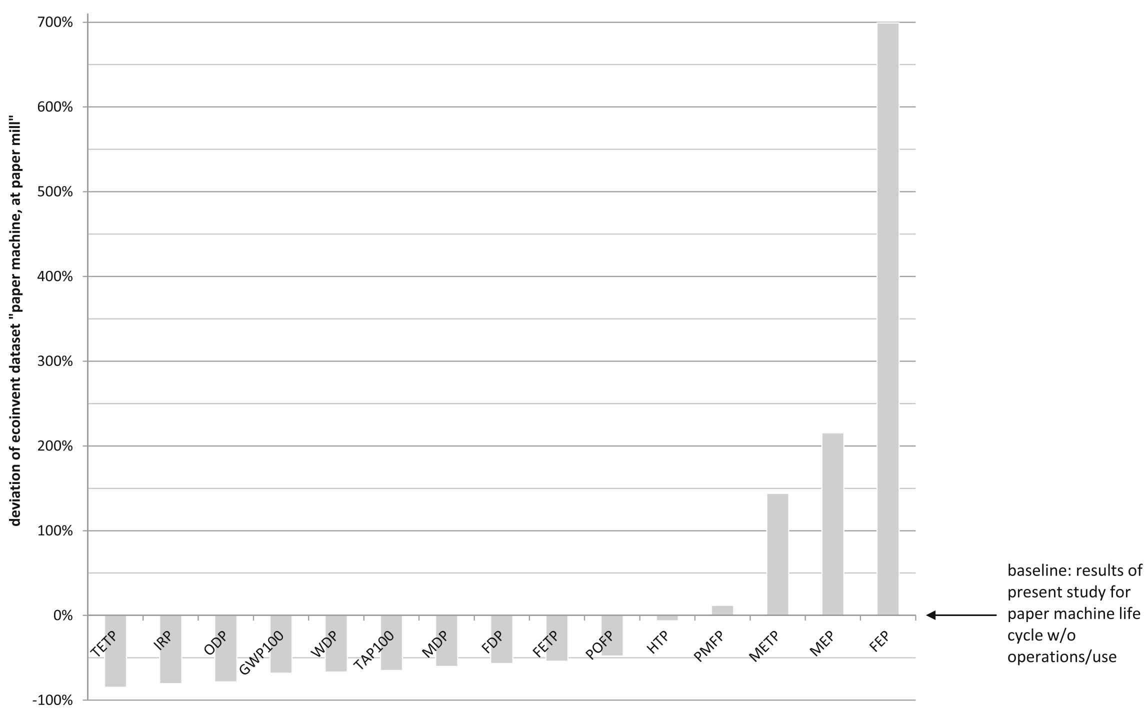

Fig. 6 Comparison of results to ecoinvent paper machine dataset

Table 4 Comparison of results to ecoinvent dataset for consumer good paper

Impact category/emission	FU=paper machine system for production of 1 t of paper			FU=1 t of paper as consumer good at plant
	CHP	GER	EU25	Newsprint paper containing DIP, ecoinvent dataset
Climate change (GWP100)	40 %	69 %	65 %	100 %
NO_x	25 %	24 %	37 %	100 %
SO_2	11 %	17 %	63 %	100 %
Ozone depletion (ODP)	−15 %	122 %	137 %	100 %
Terrestrial acidification (TAP100)	8 %	18 %	55 %	100 %
Ionizing radiation (IRP)	−3 %	27 %	42 %	100 %
Photochemical oxidant formation (POFP)	5 %	21 %	35 %	100 %
Particulate matter formation (PMFP)	4 %	16 %	42 %	100 %
Metal depletion (MDP)	23 %	24 %	24 %	100 %
Freshwater ecotoxicity (FETP)	0 %	2 %	3 %	100 %
Terrestrial ecotoxicity (TETP)	24 %	23 %	25 %	100 %
Freshwater eutrophication (FEP)	4 %	4 %	5 %	100 %
Human toxicity (HTP)	7 %	15 %	17 %	100 %
Marine ecotoxicity (METP)	0 %	2 %	3 %	100 %
Marine eutrophication (MEP)	10 %	13 %	16 %	100 %

impacts from manufacturing, transport, consumables, and end-of-life processes remain and build the baseline.[4] Figure 6 shows the deviations of the ecoinvent dataset from the defined baseline of the present study. The ecoinvent dataset results in lower impacts in most categories while still being in a comparable order indicating an underestimation in ecoinvent. Given the fact that in the present work the variety of materials considered is much larger, and the data have been directly derived from the industry, this seems highly plausible. Only for the eutrophication categories and marine ecotoxicity, the ecoinvent set leads to higher results of multiple orders. The reasons for this might be the construction activities considered in ecoinvent but could not be identified in detail. Since the ecoinvent data does not consider the operation of the machine, which has proven most important, the conclusions of the present work are not affected.

In relation to the overall environmental impacts of paper as a consumer good, Dias et al. (2007) have already shown for paper produced in Portugal and consumed in Germany that the paper production, i.e., the operation of the paper machine, is the largest contributor to CO_2 emissions (~70 %; see also Dias and Arroja 2012) as well as to acidification. It also significantly contributes to NO_x emissions.

To highlight the difference between the studied paper machine system and paper as a consumer good, Table 4 additionally compares the results of the three energy scenarios of the paper machine with results of an ecoinvent dataset on the consumer good paper for newsprint paper containing recycled fibers from DIP.[5] Accordingly, the paper grade of both systems is comparable.

Nevertheless, the relatively new ReCiPe impact categories are challenging for such a comparison. Water depletion and fossil depletion were, excluded as they did not seem to be reasonably applicable with the ecoinvent dataset because significant inventory streams are not considered for. Especially in climate change, NO_x and SO_2 emissions, the impact of the paper machine is significant compared to the paper system. Regarding the GHG and NO_x emissions, the quantitative relations are supported by the findings of Dias et al. mentioned above, which are in a consistent magnitude.

The results of the other impact categories show that for ozone depletion, acidification, and ionizing radiation, the paper machine can potentially play an important role within the larger system of the consumer good paper in dependence on the energy scenario. Metal depletion seems to be rather low for the paper machine and contradictory to the ecoinvent paper machine dataset for unknown reasons. For most toxicity related categories, the paper machine system seems to be of minor relevance. This indicates that impacts related to paper raw materials, fibers, fillers, and auxiliary chemicals which are part of the consumer good paper system contribute much more

[4] Accordingly, the scenarios for energy generation during operations/use phase do not affect the remaining results.

[5] Dataset: paper, newsprint, DIP containing, at plant, RER, #5835 (Ecoinvent 2012). The dataset consists of information from a database from Finland and data of several newsprint paper producers from Europe. The ecoinvent dataset on the consumer good paper also considers for transport to the mill site (except for wastepaper), wood processing, and wastewater treatment.

significantly to those categories than in the paper machine system, where those processes are not considered. However, the comparison should be treated very cautiously, as a bias in assumptions, regional applicability, and certainty of the compared systems might play an important role. Therefore, the paper machine operation seems to be relevant for some of the environmental impacts of paper, whereas the quantitative contribution may vary significantly with the assumptions on the paper system.

The results of this article have proven plausible and the progress has been illustrated. Overall, this leads to differentiated answers to the above defined research questions considering the relative relevance of the categories as determined by the normalization. In systems studying paper as a consumer good, considering only the impacts from the operations/use of the machine is sufficient for most impact categories, as by far most impacts are caused here (compare sectoral analysis). The manufacturing, consumables, transport, and end of life of the paper machine—as capital equipment—can then be neglected. However, if metal depletion (in part also marine ecotoxicity) is defined as an important impact category to be studied, the paper machine equipment cannot be neglected.

4.1 Limitations

By the system definition and the product description, the study is explicitly limited to the analysis of the paper machine over its life cycle. It does not seek to cover any impacts from forestry processes, pulp production, wastepaper collection, etc. that would have to be assigned to the system of paper. Furthermore, the present paper assumes a standalone paper machine, operating with 100 % recycled fibers. Hence, the results presented here are not directly applicable to integrated pulp and paper mills, which have different energy generation options including biomass residues from pulp production.

Another limitation is that no modifications or modernizations of the machine during its use are considered. In reality, paper machines and other machinery of comparable size and lifetime might be modified over time also affecting environmental performance. Quantitative influences are hardly predictable and were therefore not investigated here.

4.2 Implications

Derived from the sectoral analysis, the biggest leverage for improvements is given by the operations/use of the paper machine. Global warming and most other impact categories are almost exclusively determined by this life cycle stage. Any improvement in this phase will therefore immediately influence the overall results. Hence, OEMs should focus on optimizing the energy efficiency of their equipment, and paper producers should concentrate on operating their machinery in an energy efficient manner.

Although materials and manufacturing have shown to be of little relevance in the life cycle of a paper machine for most impact categories, the acquired results and data can still be interesting for OEMs as they are being pressured to publicly disclose environmental impacts directly caused by them during manufacturing. Especially, marine ecotoxicity could be lowered by reducing the use of copper.

The scenario analysis has proven that the type of energy generation or grid mix is crucial for global warming and other impact categories. In addition to efficiency aspects, an energetically reasonable integration of a paper machine into the energy infrastructure can have a significant influence on the environmental impacts. Therefore, more attention should be paid to higher level concepts and system engineering.

5 Conclusions

By transparently defining the paper machine operation without chemicals, additives, and fibers, this study allows for interfacing with other studies that analyze the system of paper as a consumer good. The results elaborated here based on primary industry data can then be used in other studies on newsprint from recycled paper to model paper production on a more sophisticated level than before. Nevertheless, the literature overview has shown that environmental analyses in the paper industry lack comparability due to different paper grades and differences in raw materials, recycling options, and regional aspects. A further consolidation is therefore desirable.

Within the area of capital goods, a special characteristic that has not been granted appropriate attention is the long lifetime of paper machines and most other capital equipment. Although in many cases the environmental impact of the operations will therefore exceed all other life cycle stages, it might be reasonable to put them in the center of attention. A once made decision to invest in certain capital equipment cannot be reversed easily, creating path dependencies for all final products created with the capital equipment. Then, modifications and modernization might well play an important role. These aspects can easily be overlooked when only focusing on final consumer goods.

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