Re-design of the dairy industry for sustainable milk processing

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Abstract

Within the SUSMILK project, a detailed model for energy and material flows in a dairy was developed. The LCA conducted by ESU-services identifies the relevance of energy and water uses in different process stages in a dairy from an environmental point of view. It also shows the potential of improvement options to reduce the impact of heat, cooling and electricity demand. The LCA results including a description of the goal and scope are published in this public deliverable. For the analysis of improvement options, data from project partners was collected. This life cycle inventory analysis is documented in a confidential deliverable (Jungbluth et al. 2016c).

The environmental impact of dairy processing from cradle to dairy gate was analyzed with 15 environmental impact categories (recommended by European authorities) and with the cumulative exergy demand. In addition, these category indicators were summarized to a single score applying different approaches. All recommendations are based on both result types.

Raw milk production has the highest impact from cradle to dairy gate. Thus, the production systems used for the raw milk have a decisive role for the overall environmental impact of dairy products. Raw milk supply and a reduction of milk losses at the dairy should be given priority in environmental improvement strategies. Other important aspects are the choice of packaging, wastewater treatment and raw milk transport. The impact of electricity and steam demand has to be considered as well, whereas the impact of the chemicals used for cleaning-in-place is very small.

Different improvement options that deliver heat, cooling and electricity were compared in this study. The best option is the reduction of the energy demand with a clever process design or the integration of heat exchangers.

The next best step is the replacement of existing technologies. For heating, a motor combined heat and power (CHP) plant driven by natural gas can be clearly recommended as a replacement of a natural gas boiler. If waste heat at high temperatures is available, a gas-engine driven heat pump can be recommended as well. Solar collector systems and a CHP plant driven by wood have higher environmental impacts in some environmental categories and lower in others, so that the recommendation depends on personal value choices. For solar collectors, an installation of solar collectors on flat roof is better than an installation on open ground. The share of heat delivered depends on available roof size and location (Southern Europe preferred) and thus the choice of the additional heat source is crucial. Pellet boilers cannot be recommended since they have higher environmental impacts in many environmental categories than the natural gas heating. Cooling with groundwater can clearly be recommended to replace electric cooling if no local environmental problem is affected (water temperature or scarcity). If waste heat is available, the integration of an absorption chiller can be recommended as well. If a cogeneration plant was integrated for heat delivery, an absorption chiller driven by this heat can still be recommended, though the reduction potential is less high compared to the use of waste heat.

The detailed model of dairy processes can also be used to better understand the relevance of sub-processes in the dairy and to allocate environmental impacts of processing to single products.

Kurzfassung

Im Rahmen des SUMILK-Projektes wurde ein detailliertes Modell der Stoff- und Energieflüsse für verschiedene Prozesse innerhalb einer Molkerei entwickelt. ESU-services führte eine Ökobilanz durch, welche die Umweltrelevanz von Energie- und Wassernutzung für die verschiedenen Prozessschritte analysiert. Ausserdem zeigt die Ökobilanz das Potential verschiedener Verbesserungsoptionen auf, welche die Umweltbelastung von Wärme-, Kälte- und Strombedarf reduzieren sollen. Die Resultate der Ökobilanz und die Beschreibung von Ziel und Untersuchungsrahmen sind in diesem Dokument publiziert.

Für die Analyse der Verbesserungsoptionen wurden Daten von Projektpartnern erhoben. Alle Annahmen und Sachbilanzanalyse wurde in einem vertraulichen Dokument beschrieben (Jungbluth et al. 2016c).

Die Umweltauswirkungen werden von der Wiege bis zum Molkereitor analysiert. Die Auswirkungen in 15 Umweltkategorien (empfohlen vom europäischen Forschungszentrum für Ökobilanzen) und der kumulierte Exergiebedarf werden analysiert. Zusätzlich werden die Resultate der Kategorien mit verschiedenen Ansätzen zu einem Einzelwert zusammengefasst. Beide Arten von Resultaten werden für die folgenden Empfehlungen berücksichtigt.

Der grösste Anteil der Umweltbelastung stammt aus der Rohmilchproduktion. Wie Rohmilch produziert wird spielt somit eine grosse Rolle bei den Umweltauswirkungen von Milchprodukten. Umweltstrategien sollten demnach prioritär den Rohmilch-Einkauf und die Verminderung von Milchverlusten in der Molkerei ins Auge fassen. Andere wichtige Aspekte sind die Wahl der Verpackung, Abwasserbehandlung und Transport der Rohmilch zur Molkerei. Die Umweltbelastung von Strom- und Wärmebedarf sollte auch betrachtet werden, während die Belastung durch die Chemikalien, welche für die Maschineninnenreinigung verwendet werden, sehr gering ist.

Verschiedene Verbesserungsoptionen, welche Wärme, Kälte und Strom bereitstellen, wurden in der Ökobilanz verglichen. Die beste Option ist eine Reduktion des Energiebedarfes mit einem intelligenten Prozessdesign oder durch den Einbau von Wärmetauschern.

Möglich ist auch der Ersatz konventioneller Technologien mit umweltfreundlicheren Alternativen. Für Wärme kann ein erdgasbetriebene Kraft-Wärme-Kopplung (KWK) als Ersatz für einen Erdgasboiler empfohlen werden. Wenn noch Abwärme mit genügend hoher Temperatur vorhanden ist, kann auch eine Wärmepumpe, welche mit einem Erdgasmotor betrieben wird, empfohlen werden. Solarkollektoranlagen und eine holzbetriebene KWK haben höhere Umweltauswirkungen in einigen Umweltwirkungskategorien und niedrigere in anderen. Das bedeutet, dass die Empfehlung von persönlichen Wertentscheiden abhängt. Bei den Solarkollektoren lässt sich sagen, dass eine Installation auf einem Flachdach besser ist als die Installation auf offenem Gelände. Der Anteil der Wärme, welche durch Solarkollektoren geliefert werden kann, hängt von der verfügbaren Dachfläche und dem Standort ab. Südeuropa schneidet deshalb besser ab. Auch die Wahl der zusätzlichen Wärmequelle ist relevant für eine Beurteilung von solarer Wärme. Eine Pelletheizung kann nicht empfohlen werden, weil diese in vielen Umweltkategorien höhere Umweltauswirkungen als der Erdgasboiler aufweist.

Beim Kältebedarf kann Grundwasserkühlung als Ersatz für elektrische Kühlung klar empfohlen werden, solange kein lokales Umweltproblem dadurch verursacht wird (Wassertemperatur oder –knappheit). Wenn Abwärme vorhanden ist, kann auch die Installation eines Absorptionskühlers empfohlen werden. Wenn für den Wärmebedarf ein KWK installiert wurde, kann der Absorptionskühler auch diese Wärme nutzen, wobei das Reduktionspotential im Vergleich zur Nutzung von Abwärme viel geringer ist.

Das detaillierte Molkereimodell kann auch dazu verwendet werden, die Relevanz verschiedener Unterprozesse innerhalb der Molkerei besser zu verstehen und dadurch die Umweltauswirkungen der Milchverarbeitung besser auf einzelne Milchprodukte zu verteilen.

Résumé

Un modèle détaillé des processus dans une laiterie étais développé dans le projet SUSMILK. ESU-services a réalisé une ACV afin d'évaluer et d'identifier les processus qui sont les plus important pour l'impact environnemental. L'ACV aussi montre le potentiel des différentes options qui diminue les impacts environnementaux de la mise à disposition du chauffage, du refroidissement et de l'électricité. Les résultats de l'ACV et la description de l'objectif et scope font part de ce document public.

Des données étaient recueillies des partenaires pour l'analyse des options. L'inventaire d'analyse du cycle de vie (ICV) est décrit dans un document confidentiel (Jungbluth et al. 2016c).

Les impacts environnementaux sont analysés du berceau à la porte de la laiterie (cradle to gate). Les impacts sont analysés avec 15 catégories environnementales (recommandation de l'ILCD) et avec exergie. En plus, les résultats des catégories sont résumés dans un score unique avec des approches différentes. Les deux sortes de résultat sont utilisées pour les recommandations.

Les plus grands impacts viennent de la production du lait cru. C'est la raison pour laquelle la façon de l'élevage laitier joue un rôle capital pour les impacts des produits laitiers. Les stratégies dans le cadre de l'environnement doivent faire attention à l'approvisionnement du lait et à la diminution des pertes du lait. Les autres aspects importants sont l'emballage des produits, l'épuration et le transport du lait cru jusqu'à la laiterie. Il faut prendre les impacts environnementaux de la mise à disposition de l'électricité et du chauffage aussi en considération, mais l'impact des produits chimiques utilisés pour le nettoyage en place („Cleaning-in-Place“) sont insignifiants.

Différentes options qui diminue les impacts environnementaux de la mise à disposition du chauffage, du refroidissement et de l'électricité sont analysées. La meilleure possibilité est de réduire les besoins d'énergie avec un design du processus intelligent ou avec l'installation des échangeurs thermiques.

L'option suivant et la substitution des technologies conventionnelles. Pour la chaleur, la technologie conventionnelle et un chauffe-eau opéré par gaz naturel. Le remplacement de ce chauffe-eau avec la production combinée de chaleur et d'électricité avec un moteur opéré par gaz naturel peut être clairement préconisé. S'il y en a toujours de rejets thermique, l'installation d'une pompe à chaleur opérées par gaz naturel peut être préconisée aussi. Des collecteurs solaires et la production combinée de chaleur et d'électricité opérée par bois ont des impacts élevés dans certain catégories environnementaux et moindre impacts dans des autres. A cause de ça, la recommandation dépend des valeurs personnelles. On peut dire que pour les collecteurs solaires, l'installation sur une toit et mieux que sur un champ. Le part de la chaleur qui est disponible des collecteurs solaires dépend de la superficie du toit disponible et du site (L'Europe du Sud est préférable). C'est pourquoi le choix de la source thermique additionnelle est capital. Un chauffage à granulés ne peut pas être préconisé puisque les impacts environnementaux sont élevés dans plusieurs catégories.

Pour le refroidissement, l’utilisation de l’eau souterraine peut être préconisée pour le remplacement du refroidissement électrique, si il n’y en a pas des problèmes environnementaux locaux (température ou rareté de l’eau). S’il y en a des rejets thermiques, l’installation d’un réfrigérateur de type à absorption est préconisée. Si la production combinée de chaleur et d'électricité a été installée pour la chaleur, cette chaleur peut aussi utilisée pour le réfrigérateur de type à absorption, mais le potentiel de réduction diminue comparé avec utilisation des rejets thermiques.

Un modèle détaillé des processus peut aussi être mis à profit pour analyser l’importance des différant processus dans la laiterie. Ça permet de mieux attribuer les impacts environnementaux aux différents produits laitiers.

Glossary

Cleaning-in-place (CIP)	is a method of cleaning the interior surfaces of machinery (e.g. pipes, vessels, process equipment) without disassembly.
Endpoint level	This term is used in the context of environmental impact assessment. Values at endpoint level summarize results from different impact categories respectively from the midpoint level (see below) further, i.e. to one single value.
ESU-points	An approach for normalizing and weighting environmental impact categories (15 ILCD midpoint categories and the cumulative exergy demand) to provide single score results. Normalization and weighting is based on value choices of the LCA experts at ESU-services.
Functional unit	is an exact definition of product or service that is comparable in an LCA. A functional unit can be “1 kg of cheese produced” as well as “1tkm of transported goods”.
Generic dairy model	is a model that includes the water and energy use of the main processes of a European dairy with current technologies. The details of the generic dairy model are developed in WP1 (Maga et al. 2016).
Green dairy concept	is a “green” version of the generic dairy model, where e.g. heat is provided by renewable energy instead of solely natural gas. This concept is elaborated in WP5, based on inputs from different partners including environmental information from WP7.
Improvement options	Single technologies that can replace existing technologies in the dairy and reduce environmental impacts.
Improvement scenarios	Describe the inclusion of different improvement options in the LCA generic dairy model.
LCA dairy model	is a model that is based on the generic dairy model, but that includes additional use of material, energy and water that is not considered in the generic dairy model (see Figure 3 on page 9). It includes all relevant input from cradle to dairy gate (For system boundaries, please refer to Chapter 3.2.2). The LCA dairy model is developed and documented in this deliverable.
Midpoint level	This term is used in the context of life cycle impact assessment. Midpoint level means that environmental impacts are only summarized at the impact category level (i.e. climate change or water use).

Normalization	Calculating the magnitude of category indicator results relative to reference information. Often, all emissions and resource uses during one year in a certain geographical region e.g. Switzerland, Europe or worldwide caused by one person are used as a reference. There is also the option to use an internal normalization e.g. the total emissions and resource uses of a company as a reference. The normalization factor is calculated as one divided by the reference.
Single score	The term is used if results of the environmental impact categories at midpoint level are combined to one single value with the help of normalization and weighting. Single score results are not impartial since they depend on value choices.
SUSMILK-points	An approach for normalizing and weighting environmental impact categories (15 ILCD midpoint categories and the cumulative exergy demand) to provide a single score results. Normalization and weighting is based on value choices of the partners from the SUMILK-project.
Weighting	Converts and possibly aggregates indicator results across impact categories using numerical factors based on value-choices. The weighting expresses the relative importance of different environmental indicators for the decision making. This can be based on the environmental relevance, but also on other aspects such as reliability of the indicator.

List of abbreviations

10’000.00	Number convention in the LCA part of the inventory (example: ten thousand)
BOD_5	Biochemical oxygen demand (BOD) after 5 days at 20 degrees Celsius
°C	Degree Celsius (temperatures)
CHP	Combined Heat and Power
CTUh	Comparative toxic unit for humans
CIP	Cleaning-in-place
COP	Coefficient of performance
D	Deliverable of the SUSMILK project
DE	Country code for Germany
Eq	Equivalents: fluxes with different units but with same impacts on the environment are converted to a common unit to allow summing up.
ES	Country code for Spain
FU	Functional unit
GSD	Standard Deviation 95%
GWP	Global Warming Potential
IDF	International Dairy Federation
ILCD	International Reference Life Cycle Data System
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
JRC	Joint Research Center
LCA	Life cycle assessment
LCI	Life Cycle inventory analysis
LCIA	Life cycle impact assessment
MF	Microfiltration
NF	Nanofiltration
NMVOC	Non-Methane Volatile Organic Compound
PEF	Product environmental footprint
RER	Country code for Europe (data that refers to European conditions) in the LCI
RO	Reverse Osmosis
SimaPro	Software engineered by PRé that is used to conduct life cycle assessments
SME	Small and Medium Enterprises
UF	Ultrafiltration
WMO	World Meteorological Organization
WP	Work Package

1. Introduction

This document investigates the life cycle assessment (LCA) of a theoretical dairy and possible improvement options for the supply of heat, cooling and electricity. The general methodology of LCA is described in chapter 2.

The definition of the goal and scope of the life cycle assessment was first described in the confidential Deliverable 7.1 (Jungbluth et al. 2014).

LCA is an iterative process. Parts of the goal and scope and the life cycle inventory analysis were revised in the course of the project, depending on findings during the process. Therefore the revised goal and scope of this LCA is included in Chapter 3 of this public deliverable.

The life cycle inventory analysis that documents all newly collected and compiled data sets that are used in the LCA is provided in a confidential deliverable D7.2 (Jungbluth et al. 2016c).

Chapter 4 of this report describes the detailed life cycle assessment (LCIA) for 15 category indicators according to the present recommendations by European authorities. Furthermore the cumulative exergy demand is evaluated as an additional indicator. In some cases, it was difficult to draw conclusions based on this evaluation of several impact categories. Therefore, different approaches for normalization and weighting of environmental impacts are developed in Chapter 5. These approaches facilitate the further interpretation of results.

In Chapter 6, a sensitivity analysis is performed in order to model the influence of local or regional differences for the application of certain technologies.

Results are compared with literature in Chapter 7. Furthermore, different types of analyses are interpreted and discussed here before final conclusions are provided. These conclusions are described as recommendations that aim to point out the main improvement options for dairy operation from an environmental point of view.

2. Life cycle assessment (LCA) methodology

This chapter describes the methodology of LCA.

The method of life cycle assessment (LCA) is used for the environmental evaluation within the SUSMILK project. This chapter is intended as an introduction for partners who are not familiar with the methodology of LCA and explains all important terms. These definitions and explanations will form the basis for further communication on LCA related questions. The LCA within the SUSMILK project is elaborated according to ISO standards 14040 ff but does not include a critical review. Important issues and the nomenclature from these standards are introduced in the following chapters.

2.1. Introduction

The method of life cycle assessment (LCA) aims to investigate and compare environmental impacts of products or services that occur from cradle to grave. This means that typically, the whole life cycle from resource extraction to final waste treatment is investigated.

In this LCA, the focus is on the dairy production. This is why this is not a cradle-to-grave assessment, but only encompasses the life cycle from cradle to gate. Environmental effects that occur after the milk product leaves the dairy gate are not considered. Basic principles of LCA are standardized by the International Organization for Standardization (ISO) and described in the next part.

2.2. Conceptual background in ISO 14040ff for LCA

The following description is based on the ISO standard series 14040-14049 (2006a, b) and the guidelines provided by Guinée (Guinée et al. 2001a, b). According to ISO, LCA is used for hot spot analysis, product or process improvement, comparative assertion, marketing and environmental policy. An LCA consists of four phases as illustrated in Figure 1:

- Goal and Scope Definition
- Inventory Analysis
- Impact Assessment
- Interpretation

The *Goal Definition* (phase 1) covers the description of the object of investigation. The environmental aspects to be considered in the interpretation are also defined here. The *Scope Definition* includes the way the object of investigation is modelled. Also the processes of importance towards the object of investigation are identified and described. The functional unit, which is the exact definition of the product or service that is compared, is also determined in this step[1].

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[1] A functional unit can be “1kg of cheese produced” as well as “1tkm of transported goods”.

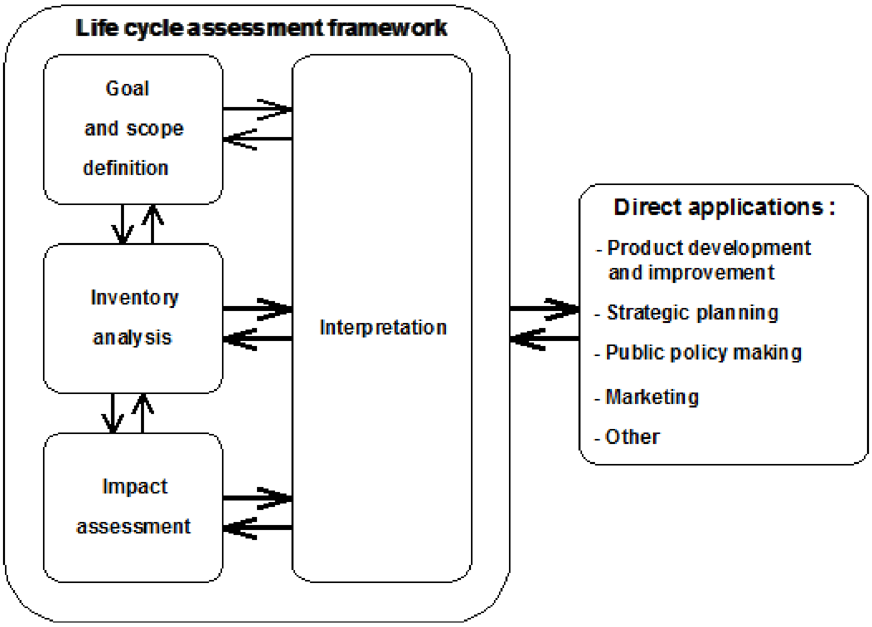

Figure 1 Components of a life cycle assessment (LCA) according to International Organization for Standardization

The direct environmental impacts[2], the amount of semi-finished products, auxiliary materials and energy of the processes involved in the life cycle are determined and inventoried in the *Inventory Analysis (LCI)* (phase 2). This data is set in relation to the object of investigation, i.e. the functional unit. The final outcome consists of the cumulative resource demands and emissions of pollutants.

The Inventory Analysis provides the basis for the *Life Cycle Impact Assessment (LCIA)* (phase 3). Current characterization methods (e.g. ILCD method) are applied to the inventory. The results are indicator values that are used and referred to in the interpretation.

The results of the inventory analysis and the impact assessment are analyzed and commented in the *Interpretation* (phase 4) according to the initially defined goal and scope of the LCA. Final conclusions are drawn and recommendations stated.

The ISO standards are not mandatory in any way for conducting LCA studies. However, it is strongly recommendable to follow the guidelines of the ISO standards as far as possible for LCA studies disclosed to the public in order to increase their credibility, especially for comparative assertions.

The following chapter describes the first step of the LCA, the Goal and Scope (Chapter 3). The LCI (Jungbluth et al. 2016c) is confidential and therefore not included. The last step (LCIA) is described in Chapter 0 ff.

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[2] Resource extraction and emission of pollutants

3. Goal and scope

The first phase of an LCA (see Chapter 2.2) that describes aim and the investigated object is described in the following chapters.

3.1. Goal of the LCA study

The following part describes why, for what and for whom this LCA is conducted and which questions the LCA should be able to answer.

3.1.1. Reason for carrying out the LCA study

The Seventh Framework Programme (FP7) of the European Commission supports transnational cooperation in research, innovation delivery and policy support across the European Union and beyond in the field of food, agriculture, fisheries and biotechnology. The objective is to build a European knowledge-based bio-economy (KBBE) by bringing together science, industry and other stakeholders, to exploit new and emerging research opportunities that address social, environmental and economic challenges[3]. The SUSMILK project is funded within FP7. The SUSMILK project addresses environmental and economic challenges in the dairy industry and more specifically in the milk processing.

3.1.2. Intended application

Based on the generic dairy model of the working package 1 (WP1), the theoretical LCA dairy model is created and evaluated in the LCA. The goal of the LCA study is an analysis of the environmental impacts of this LCA dairy model (see Chapter 3.2.1) and of possible improvement options. This comparison is then used to identify which technological developments can be integrated in the dairies in order to reduce environmental impacts. This information can be used for the development of the green dairy concept in WP5. The inclusion of improvement options into the LCA dairy model result in LCA improvement scenarios (see Chapter 3.2.1.3).

The environmental assessment is complemented by a cost analysis (Task 7.7) from Fraunhofer UMSICHT in order to give dairies a picture of the economic benefits or disadvantages of the improvement options.

An exergy-based analysis is also conducted to ensure that no optimization potential is overlooked. Exergy-based indicators include the aspect of internal losses. This analysis is elaborated in Task 7.5. It is carried out by Richtvert | Energy Systems Consultancy.

It is not planned to use the results of the study for comparative assertions between different single dairies. Nevertheless comparisons between different improvement options are elaborated. Comparisons of the environmental burdens of different dairy products are not in the focus of this study.

3.1.3. Intended audience

The targeted audience of the LCA consists of the operators of dairies, technology partners involved in the consortium and external stakeholders active in the dairy sector (e.g. equip-

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[3] Taken from http://cordis.europa.eu/programme/rcn/851_en.html, visited on 28.6.2016

ment manufacturers). In addition, the LCA will support politicians defining the needs of research and development in the dairy sector.

3.1.4. Key questions

The following key questions should be answered in this LCA study (Jungbluth et al. 2016b):

- How relevant are the energy and water uses in different process stages in the dairy from an environmental point of view?
- Which influence on the environmental impacts can be expected by implementing state of the art or new technologies developed in the SUSMILK project in existing European dairies?

3.2. Scope of the LCA study

This chapter describes the assumptions for the dairy and how the different dairy models are related to each other. Also definitions of the LCA like the functional unit, the reference year, the type and source of data, allocation procedures and LCIA methods are described in this chapter.

3.2.1. Object of investigation

The following parts state the main assumptions of the dairy and describe the dairy models considered in this LCA. All models are static models so that fluctuations during the day are not integrated (only daily demand e.g. of energy and water is considered).

3.2.1.1. *Assumptions for the generic dairy model*

The following assumptions were decided together with project partners (see Maga et al. 2014) to represent a typical dairy in the European Union.

Oberhausen in Germany is chosen as location of the dairy, which represents a location in the middle of Europe. The dairy is assumed to operate 7 days a week 24 hours per day with a raw milk input of 600’000 liter per day. The raw milk is transported by 6 refrigerated trucks that do 4 trips per day from farm to dairy. An average distance of 150 km separates the farm from the dairy so each truck covers a distance of 600 km per day. The dairy products are defined as UHT milk, cream, natural yogurt and milk concentrate, since these are the basic products of the dairy industry. In Europe, there is no standard cheese product, but many different types of cheese (fresh, soft, hard). Since these are produced in very different ways, it is not possible to model a generic cheese. Cheese and whey are not included in the generic dairy model. The energy supply is covered with natural gas and electricity from the European grid as well as diesel used for transport.

Table 1 Daily amount of milk processed and dairy products produced in the generic dairy (kg/d).

	Flow name	Amount
Milk input	Raw whole milk (4.2 % fat)	618'387
Milk products	UHT milk (3.5 % fat)	103'125
	Stirred yogurt (10 % fat)	25'959
	Cream (30 % fat)	20'022
	Concentrated milk (0.2 % fat)	121'337
	Cream (40 % fat)	29'609

Table 2 Properties of the generic dairy products

	Composition (%m/m)						
Product	Water	Fat	Protein	Carbohydrate	Ash	Sum of non-fat solids	Sum of dry matter
Raw whole milk (4.2 % fat)	87.10	4.20	3.30	4.70	0.70	8.70	12.90
Skim milk (0.05 % fat)[4]	90.87	0.05	3.44	4.90	0.73	9.08	9.13
UHT milk (3.5 % fat)	87.73	3.50	3.33	4.74	0.71	8.77	12.27
Stirred yogurt (10 % fat)	80.56	10.00	3.58	5.09	0.77	9.44	19.44
Cream (30 % fat)	63.45	30.00	2.42	3.62	0.51	6.55	36.55
Concentrated milk (0.2 % fat)	68.25	0.20	11.97	17.05	2.54	31.55	31.75
Cream (40% fat)	54.55	40.00	2.07	2.94	0.44	5.45	45.45
Water vapors	100.00	0.00	0.00	0.00	0.00	0.00	0.00

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[4] Skim milk is solely an intermediate product. It is not sold as dairy product to the consumer.

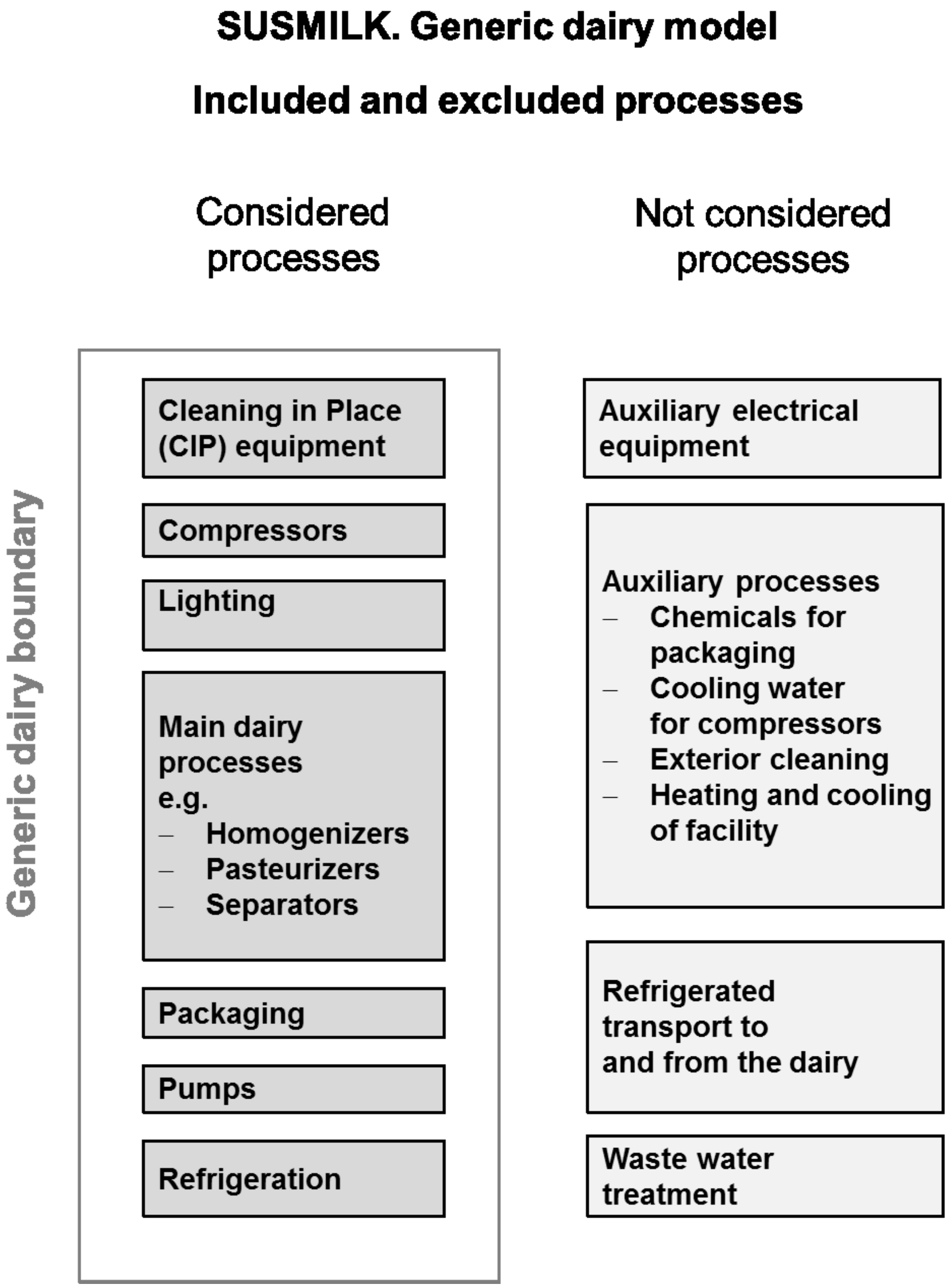

Figure 2 Scope of the generic dairy model of WP1 with included and excluded processes.

The generic dairy model includes water, energy and chemicals use for CIP of the main processes of a European dairy with current technologies. In the planning phase of the project it became clear that the participating dairies cannot provide sufficiently detailed figures for the use of energy in each processing unit. Data on the consumption of energy of their dairies is only available for the whole factory, but not for individual processes. Therefore, the generic dairy model is developed with a bottom-up method based on the inputs for the machinery needed for the different processes: CIP (water, energy and chemicals); production (steam and electricity) and refrigeration (electricity for chiller and cold stores) and packaging (electricity). Other inputs like lighting and compressed air are included as a percentage of total energy use. Data from the participating dairies and literature are used as benchmark data when developing the models. Technical information was provided by Dirk Döbbelt from Molkerei Wiegert. The details of the generic dairy model are described in the Deliverables of WP1 (Maga & Font Brucart 2016).

The resource uses of the generic dairy are shown in Table 3.

Table 3 Key figures of the generic dairy model per day and per kilogram of processed milk: energy and water use and available waste heat that can be used in the improvement options and improvement scenarios.

	Flow name	Amount	Unit	Rel. amount	Unit
Water	Fresh water	632'243	kg/d	1.02	kg/kg
Natural gas use	for production	96'772	kWh/d	0.16	kWh/kg
	for CIP	53'216	kWh/d	0.09	kWh/kg
Electricity use	for production	30'674	kWh/d	0.05	kWh/kg
	for CIP	517	kWh/d	0.00[5]	kWh/kg
Demand	Heat demand	119'990	kWh/d	0.19	kWh/kg
	Cooling demand	43'970	kWh/d	0.07	kWh/kg
Waste heat	Potentially usable waste heat	112'734	kWh/d	0.18	kWh/kg

3.2.1.2. *LCA dairy model*

The dairy model used in this LCA is based on the generic dairy model (see Figure 3). It is referred to as "LCA dairy model".

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[5] The value is 0.00084 kWh/kg. It is rounded to 0.00 in the table since the value is smaller than 0.005.

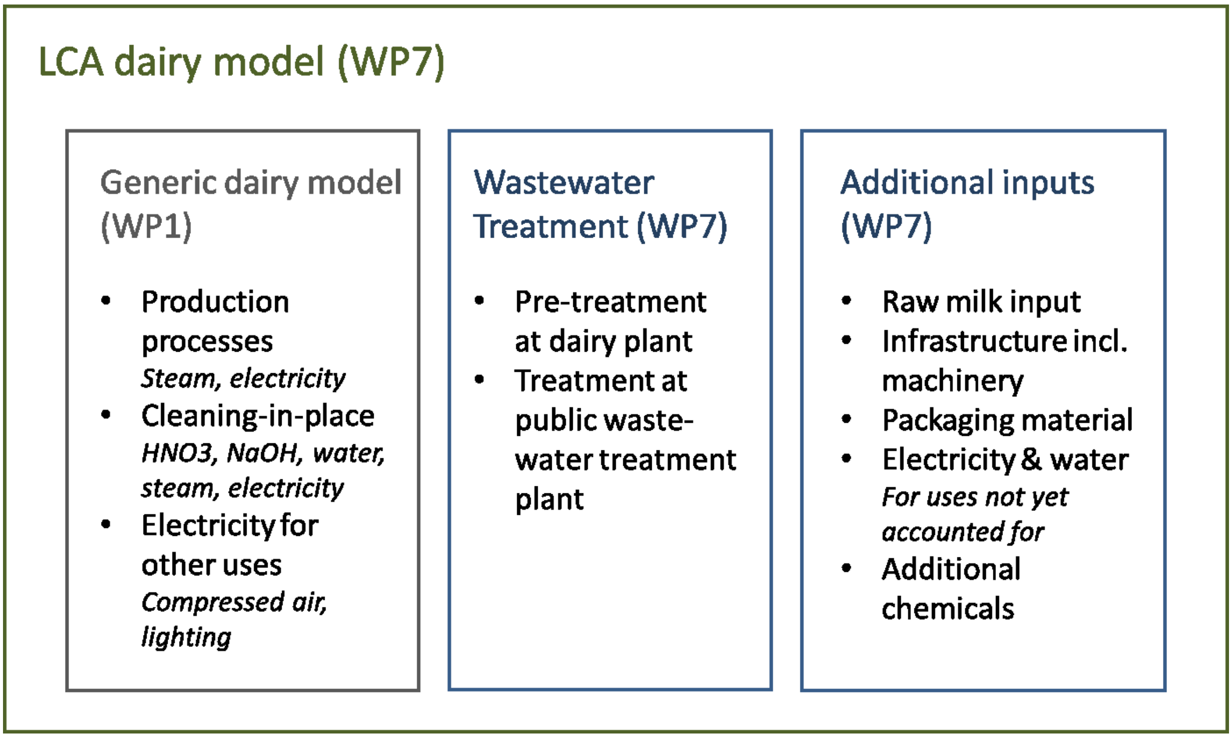

Figure 3 Composition of the LCA dairy model

Since the generic dairy model focuses on the energy and water use for the production processes, it does not take into account other material use like lubricating oil, packages or the equipment. Also additional energy and water uses are not accounted for, e.g. for toilets of the personnel (Details of the scope of the generic dairy are shown in Figure 2). Additional chemicals include refrigerants and detergents.

This is why the LCA dairy model is supplemented with materials that are not accounted for in the generic dairy model in order to provide a full picture of average environmental impacts. The main production processes of the generic dairy model are also modelled in the LCA. This allows the analysis of the contribution of the individual processes to the total energy and water use needed for processing.

Data from the participating dairies and literature are used to estimate the additional inputs. The difference between the values of the generic dairy model and the average is modelled as input for the dataset “Raw milk processing, difference average dairy to model” (see Table 4). It is added as an input to the raw milk so that it is evenly distributed to all processes. Details are described in Del. 7.2.

Table 4 The dataset “Raw milk processing, difference average dairy to model” is used to account for additional inputs. The inputs used for this dataset are shown in the last column. The average dairy data, the values of the generic dairy model, the electricity use of the wastewater pre-treatment as modelled in the LCA dairy model and the value for the difference dataset are shown in the columns from left to right.

			average dairy specific consumption	**generic dairy model**	**wastewater pre-treatment**	**Raw milk processing, difference average dairy to model**
Electricity	Electricity	kWh/kg raw milk	0.094	0.050	0.002	0.041
Heat	Total heat	kWh/kg raw milk	0.229	0.242		0
Total energy consumption	Total energy consumption	kWh/kg raw milk	0.322	0.293		0.030
	Total water use	m3/kg raw milk	0.002	0.001		0.001
Detergents	Detergents	kg/kg raw milk	0.0018			0.0018
	Nitric acid 62%	kg/kg raw milk	0.0007	0.0010		0
	Caustic soda 50%	kg/kg raw milk	0.0026	0.0036		0
	Hypochloric acid 32%	kg/kg raw milk	0.0008			0.0008
	Detergents general	kg/kg raw milk	3.90E-04			3.90E-04
	Lubricant	kg/kg raw milk	4.80E-05			4.80E-05
Wastewater	Wastewater	m3/kg raw milk	0.0017	0.0010		0.0007
Transport	Distance farm-dairy	km/trip	150	150		-
	Truck load	kg/truck	25'000	25'000		
Source			**Estimation SUSMILK**	**Model SUSMILK**	**Model SUSMILK**	**Model SUSMILK**

An overview of how the generic dairy model and the LCA dairy model are structured is shown in Figure 4. The inputs are split to the different dairy products.

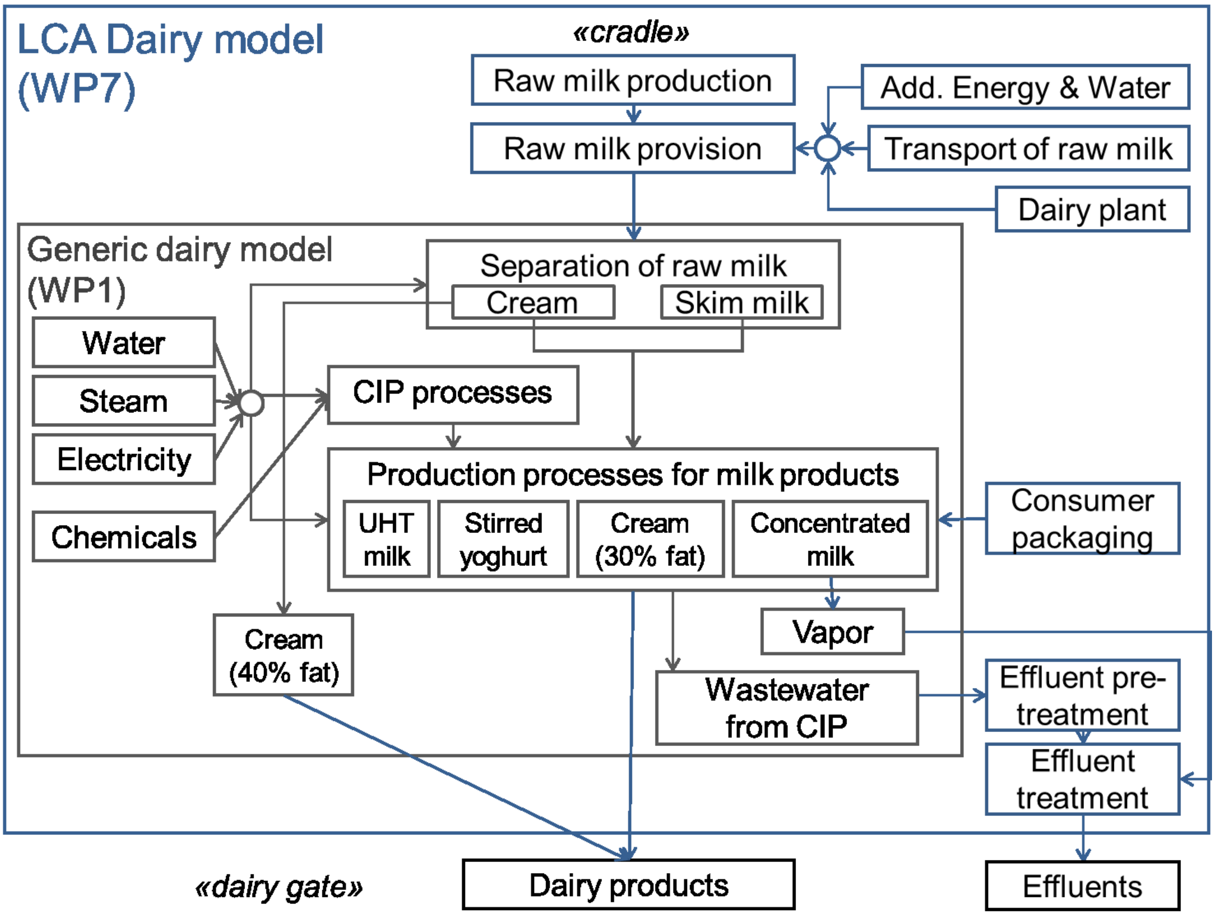

Figure 4 System boundaries and model design of the life cycle assessment on milk processing. The inputs (i.e. steam, water) are used in production processes for the different dairy products. To simplify the figure and to reduce the amount of arrows depicted, circles are used to collect and redistribute the various inputs to the five products.

3.2.1.3. *LCA improvement scenarios*

Improvement scenarios include innovative technologies (improvement options) to reduce environmental impacts. It should be possible to integrate them in the LCA dairy model. Main changes involve the energy source for heat generation and the efficiency of different technologies. The two modelled improvement scenarios are described and analyzed in Chapter 5.3.5. The following boundary conditions are maintained for this model:

- Safe and stable operation is possible over 24 hours and 365 days in a year
- The product quality is not negatively influenced by the involved technologies.

Possible improvement options for a green dairy are also developed within the SUSMILK task 5.1 and described in Azevedo (2014). These LCA models (LCA dairy model and improvement scenarios) are different from the green dairy concept from WP5. The WP5 concept outlines a vision for a green dairy in the end of the project. The LCA models provide information on the environmental impact of different improvement options and scenarios considering the whole life cycle. That information can also be used in the green dairy concept of WP5. Some scenarios within the LCA improvement options are calculated for other locations.

3.2.2. System boundaries

Since the project focuses on the milk processing at the dairy plant, a cradle-to-(dairy) gate approach is followed. The cradle-to-gate analysis refers to everything that happens until a product is ready to ship. The gate corresponds to the last processing step before the product is distributed and sold. This must not be mistaken with a cradle-to-grave analysis (see explanation of “cradle to gate” in Chapter 2.1).

Analyses are both conducted including and excluding the raw milk input. If raw milk is included, the life cycle steps included within the LCA model and the improvement scenarios are the feed cultivation, the animal husbandry and the milking at the farm as well. If raw milk is excluded, only the transport of the raw milk from farm to the dairy, the milk processing and the packaging process including the disposal of the packaging is included. The International Dairy Federation (IDF, p.14) states which processes have to be included when analyzing the processing step[6] but it does not limit them (IDF 2010, p.14f). All processes stated by the IDF are included in the LCA dairy model (Water use, wastewater treatment; use of chemicals, packaging material, energy and emissions resulting from production).

The products investigated within the cradle-to-gate system are UHT milk, stirred yogurt, cream and concentrated milk (see product portfolio in Table 1 and properties in Table 2). Cheese (and thus also whey) is not included in the generic dairy model and thus neither in the LCA models due to the lack of accurate data to estimate the flows of energy and mass that characterize its production process (see also Maga & Font Brucart 2016). Biogas from whey is only considered in laboratory scale in the SUSMILK project. The potential for this technology to be used in a dairy does not seem to be high, so that this step will neither be considered in the LCA.

The distribution and use phase of the products (using/consuming the milk products) is outside the system boundaries. This is in line with the recommendations of the IDF. They state that these transports are not specific to milk production and processing and shall not be included (IDF 2010, p.16).

The treatment of all waste occurring up to the gate and the post-consumption disposal of packages is included in the life cycle assessment in order to take all environmental impacts from cradle to gate into account. The IDF does not specifically mention the waste treatment of packaging that is included in our analysis. Since the disposal of packages is in the area of influence and responsibility of the dairy, it has been included as well.

3.2.3. Reference year

The reference year for the LCA is set to 2013. Some data might be older or newer.

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[6] The IDF guide only considers the impact on climate change (carbon footprint). In this LCA, we also consider other environmental impacts.

3.2.4. Functional units

The functional unit for the modelling of the whole dairy operation is the raw milk input into the dairy in kilogram. The reason is that the focus of the project is on the milk processing and that dairy products can have very different properties that complicate direct comparisons. Using the amount of milk processed allows using literature data that is often only available on company level. The reference flow for the modelling is the raw milk input during one day (600 000 liter raw milk) of operation for the LCA dairy model and the LCA improvement scenarios.

Another part of the assessment deals with different options for the (improved) supply of energy or water. Here the comparison is based on the energy delivered (i.e. kWh or MJ).

Single dairy products can be evaluated per kilogram leaving the dairy. The IDF recommends to state protein and fat content of products and to analyze per kg of packaged product at the dairy gate (IDF 2010, p.13). The protein and fat content is stated in Table 2 and described as part of the life cycle inventory analysis.

3.2.5. Type and source of data

In the two following chapters it is shown where modelling information stems from data collected for the project and where unspecific average data is used. The structure of the generic dairy model from WP1 and the LCA dairy model respectively the LCA improvement scenarios are shown in Figure 3.

The full life cycle inventory analysis that documents all collected and compiled unit process raw data that are used in the LCA is provided in a confidential deliverable D7.2 (Jungbluth et al. 2016c).

3.2.5.1. *Foreground data*

The data used for the LCA dairy model is based on the generic dairy model that models energy and water for processes directly connected with the dairy production as elaborated in the Deliverable 1.2 (Maga & Font Brucart 2016). Further foreground data for the LCA dairy model are based on the equipment used and described in deliverable 1.1 (Maga et al. 2014) respectively on data available in D1.2 (Maga et al. 2016) and the plant data from different dairies (Jungbluth et al. 2016c). Further foreground data is extracted from literature.

Data on the specifications on the new technical developments for the improvement options was collected by questionnaires sent to project partners. The technical innovations were still ongoing at the time of data collection, so that some data is estimated by the respective technology developers and not measured. Foreground data for additional material for the LCA improvement options are backed up and complemented by values from the literature.

3.2.5.2. *Background data*

The feed cultivation and the raw milk production are modelled with generic data from the database ESU data-on-demand for Swiss integrated agriculture (Jungbluth et al. 2016a). This data is used to assess the importance of the raw milk input for the overall results.

Other background data on the energy production is taken from ecoinvent v2.2 (ecoinvent Centre 2010) and its most recent updates on LC-inventories (LC-inventories 2016). For pellet production, data from ecoinvent v3.2 was used (Werner et al. 2014). Average European datasets are chosen for the background data of the generic dairy. If they are not available, suitable datasets (i.e. global or Swiss) are chosen. For the production of technological components for the improvement options, the country specific datasets are chosen. Where data on the technologies of the improvement options is not available, the missing inputs are estimated with internal data (Jungbluth et al. 2016a). For information on generic assumptions see Chapter 3.2.5.3.

3.2.5.3. *Generic assumptions*

In general, the LCI modelling follows the methodological guidelines of the ecoinvent database (Frischknecht et al. 2007a). For transport of the materials, ecoinvent standard distances of freight train and lorry within Europe are used. For transport of the machinery of the technological developments to the place of use, the distance between the production place and the dairy is used.

All machinery is assumed to be recycled at the end of its life. After its service life, the equipment is dismantled and the materials are recycled or disposed of. It is assumed that all metals are recycled. No environmental burdens from dismantling and recycling are included for these materials (cut-off model). Plastic parts are assumed to be burned.

3.2.6. Allocation procedures

Allocation is necessary as soon as more than one product or service is produced in the same process. Allocation describes how the inputs and outputs (respectively the environmental burden) of this process are distributed to the useful products. The definition of ISO is as follows: Allocation refers to the partition of the input and output flows of a process between the product system under study and one or more other product systems (International Organization for Standardization (ISO) 2006a).

There are some allocation procedures in the background system. The ecoinvent database uses the exergy-based allocation method as a default to allocate the input and output flows when heat and electricity are produced at cogeneration plants.

The International Dairy Federation (IDF 2010, p.18) recommends three scenarios to quantify the environmental impacts of each dairy product if the functional unit are to be defined as a specific amount of a specified dairy product:

1. Detailed processes and co-product data are available: energy and material usage as well as emissions can be directly assigned to the specific products
2. A mixture of detailed process and co-product data as well as whole of factory data are available: in this case assign detailed process and co-product data to specific products first, subtract assigned process and co-product from the factory total and then allocate the remainder based on the milk solids.
3. Only whole of factory data are on hand: apply allocation coefficients to allocate this data (e.g. total electricity, heat, water use, chemicals, etc.) to single dairy products. This approach shall be based on the physio-chemical allocation matrix developed in Australia and New Zealand to overcome the multi-functionality of dairy plants (Feitz et al. 2007).

The allocation to single dairy products in this study is made according to the descriptions above under point 2: For most processes, the generic dairy model assigns the input per product and no allocation is needed. Only the additional inputs of the LCA dairy model (see Chapter 3.2.1.2) and the inputs of the milk separation step need to be allocated. There, the allocation was conducted according to dry mass content of the two intermediate products skim milk (0.05%fat) and cream (40%fat) as suggested by the IDF (2010) and Feitz et al (2007). For all other steps, information on inputs for each dairy product is available. Other allocation procedures are described in the individual chapters.

3.2.7. Life cycle impact assessment methods

3.2.7.1. *Overview of all impact categories*

The recommended life cycle impact assessment methods in the ILCD Handbook are used in the SUSMILK project (European Commission et al. 2010). The methods at the midpoint[7] level are chosen. The methods describe potential and not measured effects related to different environmental problems. They are listed in Table 5.

Some of these indicators might be more reliable than others for the available data and the questions for this LCA. Such aspects are tackled in Chapter 5.1.2.

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[7] Midpoint level means that potential environmental impacts are characterized at the impact category level (i.e. climate change, water use). Endpoint values model these results further to a possible damage that can be added for different impact categories to one single value.

Table 5 Midpoint impact categories chosen for the SUSMILK project (Bösch et al. 2007; European Commission et al. 2010; Frischknecht et al. 2007b)

Impact category	Impact assessment model	Indicator unit	Source
Climate change	The Global Warming Potential (GWP) calculates the radiative forcing over a 100 year time horizon. It assesses the potential impact of different gaseous emissions on climate change.	kg CO_2 eq	IPCC 2007 (International Panel on Climate Change)
Ozone depletion	The Ozone Depletion Potential (ODP) calculates the destructive effects on the stratospheric ozone layer over a time horizon of 100 years. The stratospheric ozone layer reduces the amount of UV-radiation that reaches the ground and which can cause damages for humans, animals, plants and materials.	kg CFC-11 eq	WMO 1999 (World Meteorological Organization)
Human toxicity, non-cancer effects, cancer effects	The unit "CTUh" (Comparative Toxic Unit for Humans) expresses the estimated increase in morbidity in the total human population due to different types of emissions entering into the environment. The calculation is based on USEtox, which is a model that describes chemical fate, exposure, effect and optionally severity of emissions.	CTUh	Rosenbaum et al. 2008
Particulate matter	This category estimates the potential effect of fine dust emissions on human health: Quantification of the impact of premature death or disability that particulates/respiratory inorganics have on the population. It includes the assessment of primary (PM10 and PM2.5) and secondary PM (incl. creation of secondary PM due to SOx, NOx and NH3 emissions) and CO.	kg $PM_{2.5}$ eq	Humbert 2009 based on Rabl & Spadaro 2004 and Greco et al. 2007
Ionizing radiation	This category estimates the effect of radioactive emissions on human health. Most radiation stems from normal operation of nuclear power plants including the nuclear fuel production and treatment of radioactive wastes (accidents are not included). Quantification of the impact of ionizing radiation on the population is made with reference to Uranium 235.	kBq U^{235} eq (to air)	Dreicer et al. 1995
Photochemical ozone formation	This category calculates the effect of summer smog on human health. Expression of the potential contribution to photochemical ozone formation close to the ground. The method evaluates impacts on human health from ozone and other reactive oxygen compounds (LOTOS-EUROS model) developed in the lower atmosphere due to emissions e.g. of nitrogen dioxides.	kg NMVOC eq	Van Zelm et al. 2008 as appled in ReCiPe
Acidification	This impact category describes potential impacts on soil and freshwater that becomes more acid due to the deposition of certain pollutants from air: The "Accumulated Exceedance" model characterizes the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. It is European-country dependent which is not considered with the LCI data used in this study.	molc H+ eq	Posch et al. 2008 Seppälä et al. 2006
Terrestrial eutrophication	Eutrophication means that too much nutrients reach ecosystems and harm the plants and animals living in sensitive systems:	molc N eq	Posch et al. 2008 Seppälä et al. 2006

Impact category	Impact assessment model	Indicator unit	Source
	The “Accumulated Exceedance” model characterizes the change in critical load exceedance of the sensitive terrestrial area, to which eutrophying substances (“excess nutrients”) deposit. It is European-country dependent which is not considered with the LCI data used in this study.		
Freshwater eutrophication	Expression of the degree to which the nutrients emitted in Europe reach the freshwater and lead to the problem of eutrophication. Only phosphorus emissions are evaluated since it is considered as the limiting factor in freshwater. EUTREND model used to model atmospheric emissions.	kg P eq	Struijs et al. 2009 as implemented in ReCiPe
Marine eutrophication	Expression of the degree to which nutrients emitted in Europe reach the oceans and lead to eutrophication. Only nitrogen emissions evaluated since it is considered as the limiting factor in marine water. EUTREND model used to model atmospheric emissions.	kg N eq	Struijs et al. 2009 as implemented in ReCiPe
Freshwater ecotoxicity	Measurement of environmental toxicity in freshwater due to emissions: The unit “CTUe” (Comparative Toxic Unit for ecosystems) is an expression of an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg). Specific groups of chemicals require further works. (USEtox model)	CTUe	Rosenbaum et al. 2008
Land use	Land use generally refers to the amount and quality deficit of land occupied or transformed. This model is based on changes in Soil Organic Matter (SOM) due to different categories of land use. SOM is a keystone soil quality indicator and influences properties like buffer capacity, soil structure and fertility. Biodiversity impacts are not covered in this method.[8]	kg C deficit	Mila i Canals et al. 2007
Water depletion	Assessment of the water use related to local scarcity of water in different countries. (Swiss Ecoscarcity model)	m^3 water eq	Frischknecht et al. 2008
Abiotic resource depletion	The model covers mineral, fossil & renewable resource depletion. The model takes both the annual production as well as the availability of the resource into account. (CML 2002 model)	kg antimony (Sb) eq	van Oers et al. 2002
Cumulative exergy demand	Exergy is a measure for the useful "work" a certain energy carrier can offer. In this impact assessment, exergy is used as a measure of the potential loss of "useful" energy resources. The characterisation is based on the accounting of energy and other resources in ecoinvent. It includes the exergy of energy carriers as well as of non-energetic resources like minerals and water[9].	MJ-eq	Bösch et al. 2007

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[8] The LCIA method in SimaPro has assigned characterisation factors for elementary flows of land use in the ocean „benthos“. These factors have been removed after consulting the authors of the method as they are not meaningful.

[9] The solar energy uptake of solar collectors was adapted to account only for the exergy of hot water. See Chapter 3.2.7.6 for details.

3.2.7.2. *Long-term emissions*

Some indicators are strongly dependent on long-term emissions. Such long-term emissions can only be modelled in a quite unreliable way. Some databases such as ecoinvent investigate long-term emissions of heavy metals and other pollutants (Frischknecht et al. 2007a). These emissions can take place in a time frame of 100 to 60'000 years from now. They mainly stem from waste disposal in landfills and deposits made during mining of metals.

If these long-term-emissions are included in the LCIA they can make up a considerable amount of the total impacts in the ILCD impact categories. The analysis of the heating options (datasets from Chapter 4.3.1 are analyzed) shows that in five categories, a considerable part of total impacts solely stems from the long-term emissions if they are included in the LCI:

- Human toxicity, non-cancer effects: 50 to 80%
- Human toxicity, cancer effects: 4 to 80%
- Ionizing radiation HH: around 70% for all datasets
- Freshwater eutrophication: 30 to 90%
- Freshwater ecotoxicity: 40 to almost 100%

If long-term emissions are included in the assessment, background data on e.g. machinery become very relevant, but it is nearly impossible to check the appropriateness of this data.

An extensive discussion about the pros and cons of including long-term emissions in LCIA can be found in the Ecoinvent report on LCIA methods (Frischknecht et al. 2007b). It was decided in WP7 to exclude long-term emissions in the life cycle impact assessment because of the high uncertainties involved. This is also in line with internal findings of the PEF studies unfortunately not yet published.

3.2.7.3. *Photochemical ozone formation*

Ozone and other reactive oxygen compounds are formed as secondary contaminants in the troposphere (close to the ground). Ozone is formed by the oxidation of the primary contaminants VOC (Volatile Organic Compounds) or CO (carbon monoxide) in the presence of NOx (nitrogen oxides) under the influence of light. The method used includes spatial differentiation and is only valid for Europe.

3.2.7.4. *Abiotic resource depletion*

This impact category indicator assesses extraction of metals, minerals and fossil fuels. The Abiotic Depletion Factor (ADF) is determined for each of these extraction materials and related to the scarcity of antimony (Unit: kg antimony equivalents/kg extraction) based on concentration reserves and rate of deaccumulation. By including the annual production, the current importance of a give resource is also reflected. The scarcity of resources is determined based on the 'Reserve base'. It refers to identified resources that meet specified minimum physical and chemical criteria related to current mining practice. Therefore it may contain those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics.

3.2.7.5. *Ecotoxicity freshwater*

The impact category ecotoxicity freshwater assesses the heavy metals and pesticides. The characterization factors for the heavy metals are classified as "uncertain" while the ones for the pesticides are "recommended". It would be possible to separate the assessment of the heavy metals in order to better interpret the impact assessment of the pesticides. But in the course of this project this is not of importance.

3.2.7.6. *Exergy analysis*

Exergy analysis is used as an additional method of analysis. The cumulative exergy consumption is therefore added to the list of midpoint indicators in order to cross-check the results of the LCA and exergy analysis based on the method developed in the ecoinvent database and the LCI data of the LCA (Bösch et al. 2007; European Commission et al. 2010 Frischknecht et al. 2007b).

Subcategories

The cumulative exergy demand is split into different subcategories to discriminate between different types of renewable and non-renewable origins. They are listed Table 6.

Table 6 Explanation for the sub-categories of the cumulative exergy demand

Sub-category	Explanation
Non-renewable, fossil	Exergy content of fossil resources like coal, crude oil, natural gas, peat and others (chemical energy)
Non-renewable, nuclear	Energy from uranium converted in the technical system (nuclear energy)
Renewable, kinetic (wind)	Energy from wind converted in the technical system (kinetic energy)
Renewable, solar	Energy from the sun converted in the technical system (radiative energy)
Renewable, potential (water)	Energy from hydropower reservoir (potential energy)
Non-renewable, primary forest	Exergy content of wood from primary forests (chemical energy)
Renewable, biomass	Exergy content of other wood sources (chemical energy)
Renewable, water	Exergy content of extracted fresh water minus released water (chemical energy)
Non-renewable, metals	Exergy content of metal resources (chemical energy)
Non-renewable, minerals	Exergy content of mineral resources (chemical energy)

General differences of this indicator compared to the exergy analysis in this project

This indicator applies characterization factors for exergy based on elementary flows that are derived from a life cycle inventory analysis. This method can provide different results than the detailed exergy analysis of Andrej Jentsch from Richtvert | Energy Systems Consultancy, since the LCI exergy analysis includes partially different assumptions than those documented in the exergy analysis part of D7.3. Significant differences in exergy analysis results between both analysis approaches will be discussed in the exergy analysis part of D7.3. The exergy indicator used for the LCA only accounts for resource input, but it does not check if resources are lost (e.g. because they are burned) or only transformed (e.g. use of crude oil for plastics). Therefore, impacts from such material uses might be overestimated as the exergy is still available in the material and not lost. Furthermore, cooling or heating of water, air and soil is not covered in the method that can be applied on LCI data.

Adjustment of exergy of solar collector

The exergy method described in this study does not differentiate between solar energy used to produce hot water or electricity, assigning 1MJ exergy per MJ of energy in both cases. Therefore results of the solar collectors are based on an improved exergy assessment method. In this instead of considering renewable, solar energy as the input for the balance boundary, its first storable product (electricity, warm water) is considered to be the "primary energy". This is an effective approach that allows compensating for the fact that natural gas originally also has been mainly solar energy (Jentsch 2010). In the case below this means that the solar exergy values from the basic method have been multiplied by factor 0.12. This equals the exergy to energy ratio of hot water with an average temperature of 50 °C at a reference temperature of 10 °C produced by the solar collectors.

3.2.7.7. *Normalization and weighting of environmental impacts*

An own approach for normalization and weighting of environmental impacts is developed in chapter 5.

4. Life cycle impact assessment

4.1. Words to describe range of values

To describe the relative difference of two values in a consistent way, the words to be used are defined here. They refer to a relative difference of a value to the reference value, i.e. the value of A is 300% higher than the value of B, which means that A is extremely higher than B. If the values are lower, than the equivalent factors are used, i.e. if a factor 4 (+300%) higher means “extremely higher”, than a division by a factor 4 (-75%) means “extremely lower”.

The comparison of an improvement option with the option used in the generic dairy does not directly reveal the importance of an environmental problem. Some issues like land use might e.g. not be very relevant for the conventional technology used as the reference, so that a new technology might have extremely higher impacts. Extremely higher values should be taken as a warning for further evaluation if this really is a relevant problem of the new technology, but they do not describe the importance of the environmental impact.

Table 7 Definition of words to describe the relative difference of a value compared to a reference value. The values in the tables are formatted in the way shown here.

Description	Range of values if higher	Range of values if lower
In the same range	0 up to +10%	0 to -9%
A bit higher / lower	+10 up to +40%	-9 to -29%
Higher / lower	+40 up to +100%	-29 to -50%
Considerably higher / lower	**+100 up to +300%**	-50 to -75%
Extremely higher / lower	**higher than +300%**	**lower than -75%**

4.2. Analysis of operation of the generic dairy

4.2.1. Analysis of process stages

Processes in the LCA software SimaPro are summarized into groups that represent process stages. That way, the contribution of the process stages to the total impact can be assessed. Table 8 shows the definition of these groups in SimaPro. This definition is used for the further analysis of the LCA dairy model.

Table 8 Definition of groups in SimaPro that represent process stages: The name of the process stage, the description of the main inputs and the exact name of the included processes is listed. Bold processes are part of the generic dairy model.

Name of the group	Description	List of the included processes
Raw milk production	Input of raw milk for processing; purchased products not included	Raw whole milk (4.2 % fat)
Purchased products; dairy plant; additions	Purchased ingredients, infrastructure of dairy plant, additional impacts of processing considered with literature data (not including transport to dairy, milk itself or additional electricity)	**Potato starch;** **Milk powder;** dairy plant; Raw milk provision
Transport of raw milk	Refrigerated transport of raw milk to the dairy	refrigerated transport, chilled goods, road
Effluent (pre-)treatment	Treatment of wastewater inside and outside the dairy, but not including electricity for pre-treatment	Pre-treatment in the dairy; treatment, dairy effluent; vapors treatment
Consumer packaging	Product packaging (Production and disposal, excluding direct electricity use for packaging),)	packaging 1l milk, tetra brick; use, polypropylene-forms
Electricity, additional	Additional energy use according to the LCA dairy model	Electricity, additional average dairy
Electricity	Electricity use according to generic dairy model, including electricity use for packaging process	**Electricity**
Steam for production	Heat use delivered by steam	**Steam for heating**
Steam for CIP	Steam used for cleaning the machinery internal	**Steam for disinfection**
Chemicals	Chemicals used for CIP	**HNO_3 70%; NaOH 50%**
Water use	All inputs needed for water use, including cooling water and infrastructure, but without the electricity use	**Cold water; Ice water; Water; Deionized water; water, completely softened**

4.2.2. With raw milk supply

The analysis of the generic dairy in Figure 5 shows that in all impact categories, the raw milk production has the highest influence on the total impact. In the impact categories water depletion and ozone depletion, the share of the processing is close to 50%. For the ozone depletion, refrigerant losses for cooling within the dairy and for the raw milk transport and the transport of natural gas both have a considerable impact (each around 15% of total). The results in percent are given in Table 9.

Refrigerated transport

The analysis of the refrigerated transport shows that almost 90% of the impact stems from the transport itself, whereas the extra diesel used for refrigeration contributes less than 10%. Only a small fraction of the impact is due to refrigerants.

Positive results of raw milk for human toxicity

When raw milk is included in the assessment, the impact category Human toxicity, non-cancer effects shows negative values which mean a positive effect on the environment. This effect stems from the raw milk production respectively from growing of feed for the livestock. There, the uptake of zinc and lead from the ground by maize respectively lead, mercury and zinc by plants on meadows add up to a positive effect. These values are very uncertain. The pathways of metals in soil are part of a complex system, where deposition from air and input from fertilizer, washing out and uptake from plants play a role. If the metals are not taken out of the cycle, but end up in the soil again, e.g. because the manure of the cows is used as fertilizer, then this positive effect on the environment cannot be defended. Therefore, these uncertain values do not mean that milk has in general a positive effect on human toxicity.

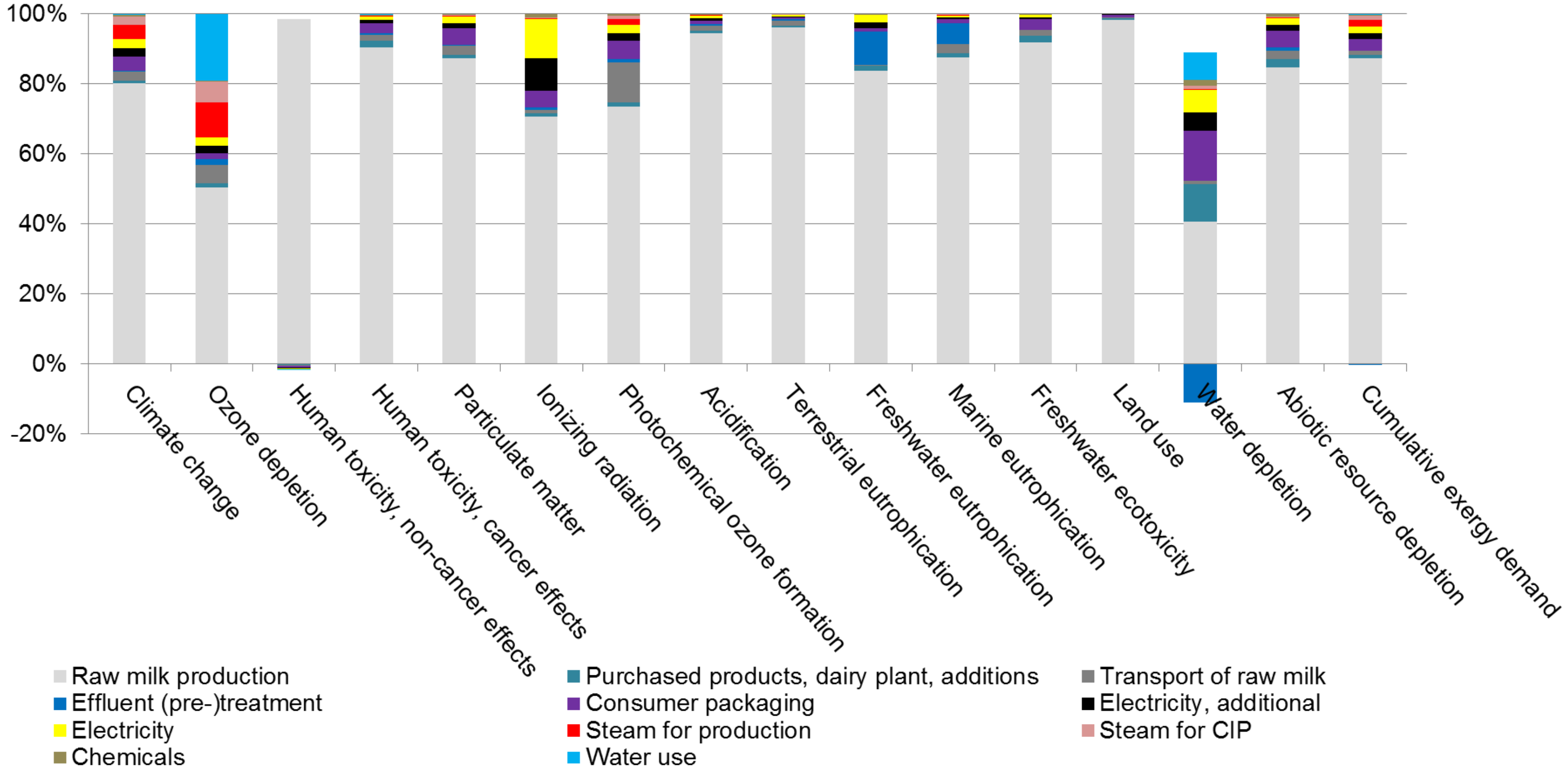

Figure 5 ILDC impact categories and cumulative exergy demand: Analysis of LCA dairy model including the raw milk production. The share of each group (defined above in “analysis of groups”) on the total impact in each category is given in percent (value of group divided by value of total impact). Since some values are minus in the categories water depletion (effluent (pre-)treatment) and human toxicity, non-cancer effects (raw milk production and total), some shares are also minus.

Table 9 ILCD impact categories: Share of product stages on total impact of dairy plant operation

Impact category	Raw milk production	Purchased products, dairy plant, additions	Transport of raw milk	Effluent (pre-) treatment	Consumer packaging	Electricity, additional	Electricity	Steam for production	Steam for CIP	Chemicals	Water use
Climate change	80.15%	0.88%	2.44%	0.33%	4.08%	2.27%	2.68%	4.11%	2.31%	0.46%	0.30%
Ozone depletion	50.52%	1.09%	5.34%	1.58%	1.66%	2.06%	2.44%	10.17%	5.76%	0.30%	19.08%
Human toxicity, non-cancer effects	101.60%	-0.26%	-0.24%	-0.09%	-0.45%	-0.16%	-0.18%	-0.04%	-0.02%	-0.15%	-0.02%
Human toxicity, cancer effects	90.44%	1.86%	1.63%	0.51%	3.04%	0.77%	0.91%	0.27%	0.18%	0.23%	0.17%
Particulate matter	87.44%	0.83%	2.56%	0.42%	4.76%	1.44%	1.70%	0.33%	0.19%	0.27%	0.04%
Ionizing radiation	70.60%	0.94%	1.10%	0.59%	4.91%	9.33%	11.02%	0.34%	0.24%	0.81%	0.13%
Photochemical ozone formation	73.61%	1.03%	11.52%	1.05%	5.19%	2.03%	2.40%	1.69%	0.96%	0.46%	0.06%
Acidification	94.60%	0.69%	1.36%	0.43%	0.99%	0.67%	0.79%	0.20%	0.12%	0.14%	0.02%
Terrestrial eutrophication	96.09%	0.66%	1.44%	0.43%	0.51%	0.24%	0.28%	0.16%	0.09%	0.10%	0.01%
Freshwater eutrophication	83.70%	1.53%	0.27%	9.42%	0.97%	1.71%	2.01%	0.08%	0.05%	0.22%	0.03%
Marine eutrophication	87.64%	1.20%	2.56%	6.08%	1.06%	0.42%	0.49%	0.28%	0.16%	0.12%	0.01%
Freshwater ecotoxicity	91.80%	2.01%	1.55%	0.21%	2.93%	0.52%	0.61%	0.09%	0.06%	0.16%	0.05%
Land use	98.29%	0.53%	0.17%	0.02%	0.83%	0.03%	0.04%	0.04%	0.03%	0.01%	0.01%
Water depletion	52.20%	13.46%	1.45%	-13.98%	18.13%	6.82%	8.05%	0.31%	1.38%	1.94%	10.24%
Abiotic resource depletion	84.64%	2.45%	2.50%	0.75%	4.91%	1.64%	1.94%	0.24%	0.16%	0.63%	0.13%
Cumulative exergy demand	87.59%	0.83%	1.24%	-0.11%	3.51%	1.59%	1.88%	1.96%	1.12%	0.20%	0.20%

Table 10 ILCD impact categories: Absolute results of product stages of dairy plant operation

Impact category	Unit	Total	Raw milk production	Purchased products, dairy plant, additions	Transport of raw milk	Effluent (pre-) treatment	Consumer packaging	Electricity, additional	Electricity	Steam for production	Steam for CIP	Chemicals	Water use
Climate change	kg CO2 eq	564'117	452'124	4'947	13'763	1'881	23'025	12'815	15'133	23'183	13'004	2'571	1'672
Ozone depletion	kg CFC-11 eq	0.0287	0.0145	0.0003	0.0015	0.0005	0.0005	0.0006	0.0007	0.0029	0.0017	0.0001	0.0055
Human toxicity, non-cancer effects	CTUh	-0.4546	-0.4619	0.0012	0.0011	0.0004	0.0020	0.0007	0.0008	0.0002	0.0001	0.0007	0.0001
Human toxicity, cancer effects	CTUh	0.0112	0.0102	0.0002	0.0002	0.0001	0.0003	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
Particulate matter	kg PM2.5 eq	279.63	244.51	2.33	7.15	1.18	13.32	4.03	4.76	0.92	0.54	0.76	0.12
Ionizing radiation	kBq U235 eq	34'573	24'409	323	381	202	1'699	3'225	3'808	119	84	279	44
Ionizing radiation E (interim)	CTUe	0.2935	0.2026	0.0028	0.0032	0.0018	0.0149	0.0291	0.0344	0.0011	0.0007	0.0025	0.0004
Photochemical ozone formation	kg NMVOC eq	1'207.40	888.81	12.43	139.12	12.69	62.64	24.52	28.95	20.39	11.54	5.59	0.73
Acidification	molc H+ eq	8'469.79	8'012.02	58.76	115.05	36.22	83.95	56.73	66.99	17.19	9.87	11.74	1.29
Terrestrial eutrophication	molc N eq	36'273.05	34'853.54	239.75	523.60	154.45	186.24	86.08	101.64	57.03	32.38	35.77	2.58
Freshwater eutrophication	kg P eq	68.04	56.95	1.04	0.19	6.41	0.66	1.16	1.37	0.05	0.03	0.15	0.02
Marine eutrophication	kg N eq	1'865.97	1'635.32	22.31	47.68	113.39	19.83	7.75	9.16	5.20	2.95	2.15	0.23
Freshwater ecotoxicity	CTUe	496'614	455'900	9'984	7'713	1'035	14'550	2'584	3'051	449	293	800	256
Land use	kg C deficit	13'697'531	13'462'895	73'199	23'877	3'115	113'626	4'132	4'879	6'056	3'518	1'269	964
Water depletion	m3 water eq	1'041	543	140	15	-145	189	71	84	3	14	20	107
Abiotic resource depletion	kg Sb eq	2.93	2.48	0.07	0.07	0.02	0.14	0.05	0.06	0.01	0.00	0.02	0.00
Cumulative exergy demand	MJ	19'157'245	16'779'825	158'282	237'597	-21'584	671'782	304'740	359'854	375'584	215'008	38'042	38'114

4.2.3. Without raw milk supply

In this chapter, the processing in the dairy is analyzed further by excluding the production of raw milk at the farm (see Figure 6). The shares of total impact in percent are shown in Table 11, whereas the absolute values are given in Table 10 in the chapter above.

4.2.3.1. *Analysis of process stages*

If raw milk is excluded from the analysis, the crucial input group depends on the impact category (see Figure 6). The transport of raw milk (refrigeration truck) shows the highest share for acidification, ozone formation and terrestrial eutrophication. The consumer packaging has considerable shares in land use, particulate matter, abiotic resource depletion and all toxicity categories. Not surprisingly, the effluent treatment is most important for marine and freshwater eutrophication. The chemicals used for cleaning (NaOH, HNO_3) have very little effect compared to the other groups (maximum of 9%).

In the impact category climate change, one of the two main impacts stem from packaging of the UHT milk and cream (30% fat) which amount to 20% of the total. When analyzing the packaging, around half of its impact stems from production and disposal of the plastic part and less than 20% each stem from the production of aluminum foil and cardboard. The other main impact is steam for production (20%), followed by steam for CIP (10%).

In the impact category water use, around 40% stems from packaging. For the Tetra Brik, the water use stems from paper production, for the polystyrene packaging of the yogurt, the cooling water used for thermoforming has the main impact. Almost 30% stems from additional water and electricity use that is not accounted for in the generic dairy model (Details on the LCA dairy model can be found in Chapter 3.2.1.2). The discharge of water after the effluent treatment shows a negative percentage since it decreases water depletion. The water in the effluent stems from vapors from concentrated milk and from CIP. Water input for CIP is shown in the process stage “water use” and amounts to 21% of total impact.

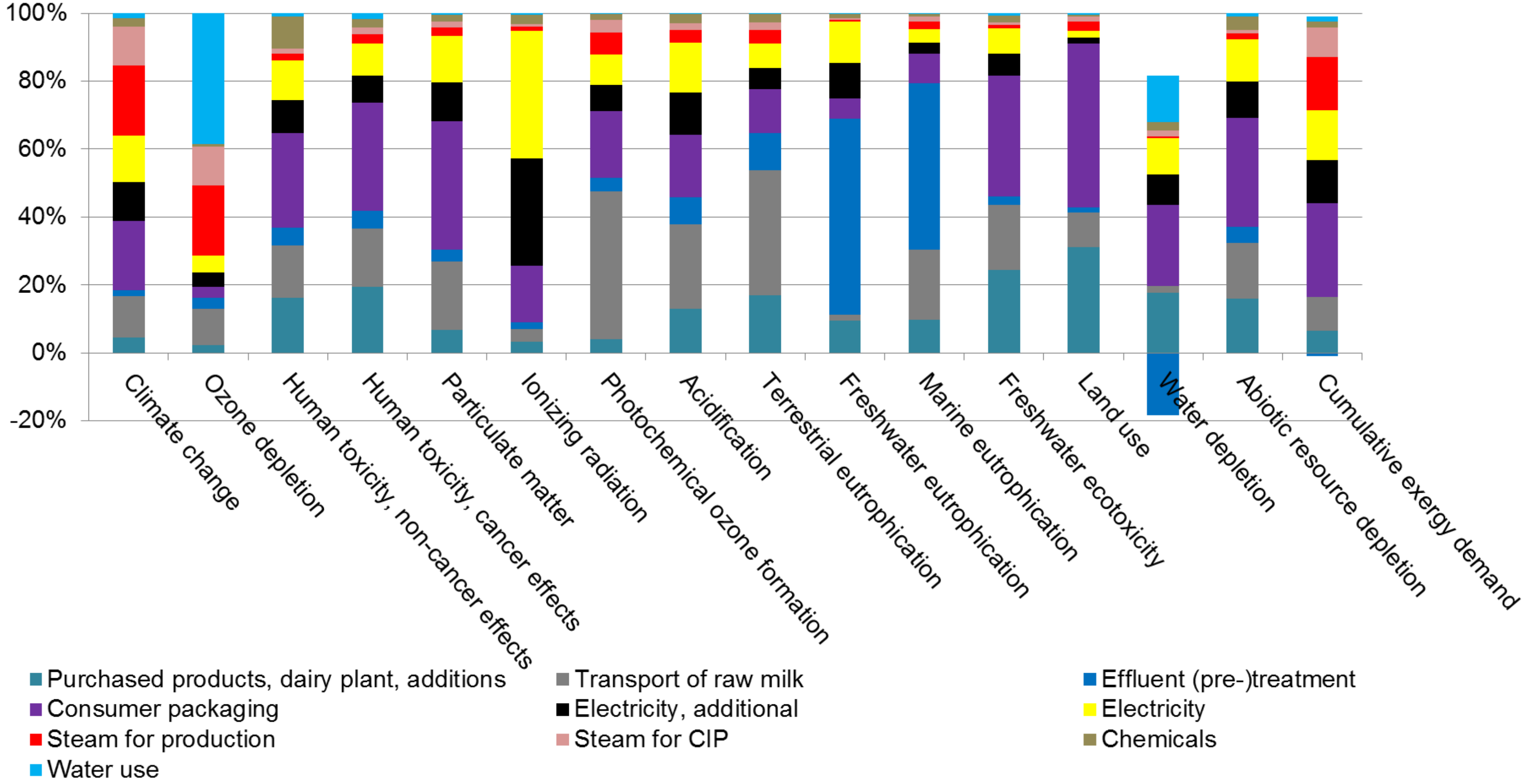

Figure 6 ILCD impact categories and cumulative exergy demand: Analysis of LCA dairy model without the raw milk production. The share of each group (defined above in “analysis of groups”) on the total impact in each category is given in percent. All shares above the black group stem from the generic dairy model, all shares from the black bar to the bottom stem from the additional inputs included in the LCA dairy model.

Table 11 Share of product stages on total impact of dairy plant operation without raw milk production. The higher the share, the darker the grey shade.

	Purchased products, dairy plant, additions	**Transport of raw milk**	**Effluent (pre-) treatment**	**Consumer packaging**	**Electricity, additional**	**Electricity**	**Steam for production**	**Steam for CIP**	**Chemicals**	**Water use**
Climate change	4.4%	12.3%	1.7%	20.6%	11.4%	13.5%	20.7%	11.6%	2.3%	1.5%
Ozone depletion	2.2%	10.8%	3.2%	3.3%	4.2%	4.9%	20.6%	11.7%	0.6%	38.6%
Human toxicity, non-cancer effects	16.2%	15.3%	5.4%	27.9%	9.7%	11.5%	2.2%	1.5%	9.3%	1.0%
Human toxicity, cancer effects	19.5%	17.1%	5.3%	31.8%	8.0%	9.5%	2.8%	1.8%	2.4%	1.8%
Particulate matter	6.6%	20.4%	3.4%	37.9%	11.5%	13.6%	2.6%	1.5%	2.2%	0.3%
Ionizing radiation	3.2%	3.8%	2.0%	16.7%	31.7%	37.5%	1.2%	0.8%	2.7%	0.4%
Photochemical ozone formation	3.9%	43.7%	4.0%	19.7%	7.7%	9.1%	6.4%	3.6%	1.8%	0.2%
Acidification	12.8%	25.1%	7.9%	18.3%	12.4%	14.6%	3.8%	2.2%	2.6%	0.3%
Terrestrial eutrophication	16.9%	36.9%	10.9%	13.1%	6.1%	7.2%	4.0%	2.3%	2.5%	0.2%
Freshwater eutrophication	9.4%	1.7%	57.8%	5.9%	10.5%	12.4%	0.5%	0.3%	1.3%	0.2%
Marine eutrophication	9.7%	20.7%	49.2%	8.6%	3.4%	4.0%	2.3%	1.3%	0.9%	0.1%
Freshwater ecotoxicity	24.5%	18.9%	2.5%	35.7%	6.3%	7.5%	1.1%	0.7%	2.0%	0.6%
Land use	31.2%	10.2%	1.3%	48.4%	1.8%	2.1%	2.6%	1.5%	0.5%	0.4%
Water depletion	28.2%	3.0%	**-29.2%**	37.9%	14.3%	16.9%	0.6%	2.9%	4.1%	21.4%
Abiotic resource depletion	16.0%	16.3%	4.9%	31.9%	10.7%	12.6%	1.6%	1.0%	4.1%	0.8%
Cumulative exergy demand	6.7%	10.0%	-0.9%	28.3%	12.8%	15.1%	15.8%	9.0%	1.6%	1.6%

4.2.3.2. *Analysis of products share*

The split of the impacts of the dairy operation to the different products produced is shown in Figure 7. The daily production amount of dairy products in the generic dairy (kg per day) influences this share and is shown in Chapter 3.2.1.1. Concentrated milk is the product with highest production amount and also has the largest share of the environmental impact in most categories. The amount of UHT milk produced is about 20% less than of concentrated milk, but its share on the impact is less than half as much.

The direct milk input is excluded, but the input of purchased dairy product is still included in the analysis. For the production of yogurt, milk powder is added. The LCIA values of milk powder are negative, which means the values are describing a positive effect on the environment in the category human toxicity, non-cancer effect (see Chapter 4.2.1). This this leads to a net negative LCIA value for yogurt in this category. The share of total environmental impact of yogurt on total impact of dairy operation of this specific impact of the dairy.

There are some differences concerning the shares of products on total impact of dairy operation in different impact categories. Cream (30%) and UHT milk have a higher share in the category land use, stemming from Tetra Brik used for packaging (both around 90% of total product impact). The origin of the impact is the land needed for wood production to produce the cardboard. For yogurt, the impact on land use stems from milk powder (90%) and originally from fodder production for the cows. Only little stem from the packaging for yogurt (polystyrene packaging contributes less than 5%). Cream (40%) and concentrated milk have a lower share concerning land use because they are sold to other dairies without consumer packaging.

The relative high share for ozone depletion for concentrated milk is due to the amounts of cooling and heat energy needed for this product. More than two third of total cooling demand and heat demand of the dairy is used to produce concentrated milk. The origin of the calculated impact for heat is the transport of natural gas. There, bromochlorodifluoromethane is emitted. For cooling, the losses of refrigerants are the main impact.

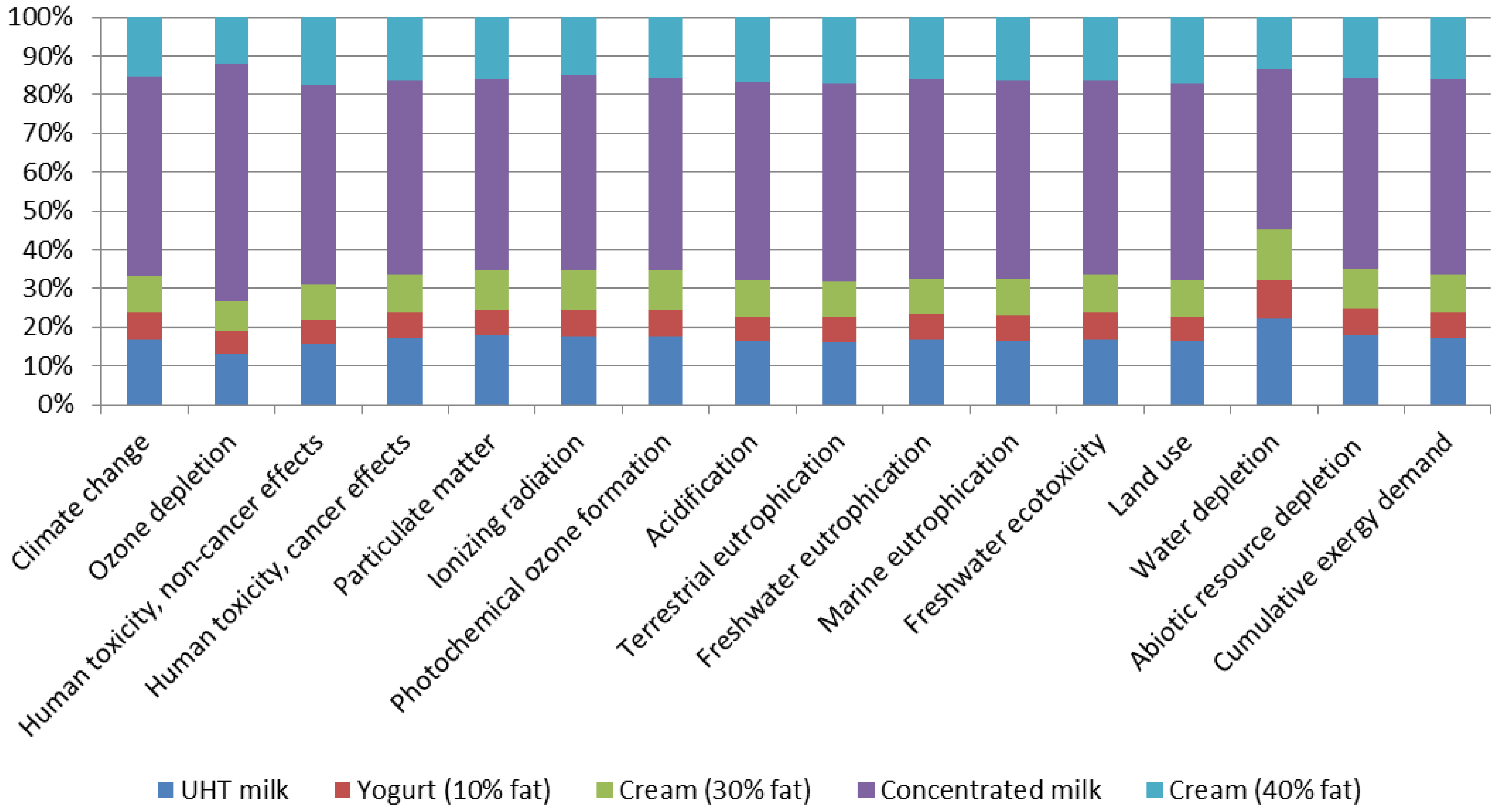

Figure 7 ILDC impact categories: Relative impact of each dairy product as a share of total impact of the dairy operation (amount of products produced per day are described in goal & scope) in each category. The dairy operation is assessed without raw milk production.

4.2.4. Product analysis

4.2.4.1. *ILCD impact categories*

The share of milk production on total impact per kilogram of the four dairy products is shown Figure 8. When analyzing different milk products, milk production has by far the highest share of environmental impact in all categories except water use. For the different products considered, the shares of the milk production of total impact do not deviate much.

Since the packaging of the products contributes a lot to the total impact of processing, the packed cream and yogurt (small packages) have the highest impact of all products in many categories (see Figure 8).

In the category human toxicity, non-cancer effects, the share of raw milk production on total impact is slightly more than 100%. This is because the calculation of the effect in this impact category leads to negative values (i.e. positive effects on the environment, see end of Chapter 4.2.1), the operation gives positive values and the sum of both still has negative values. Therefore, the share of the raw milk on total is higher than 100%.

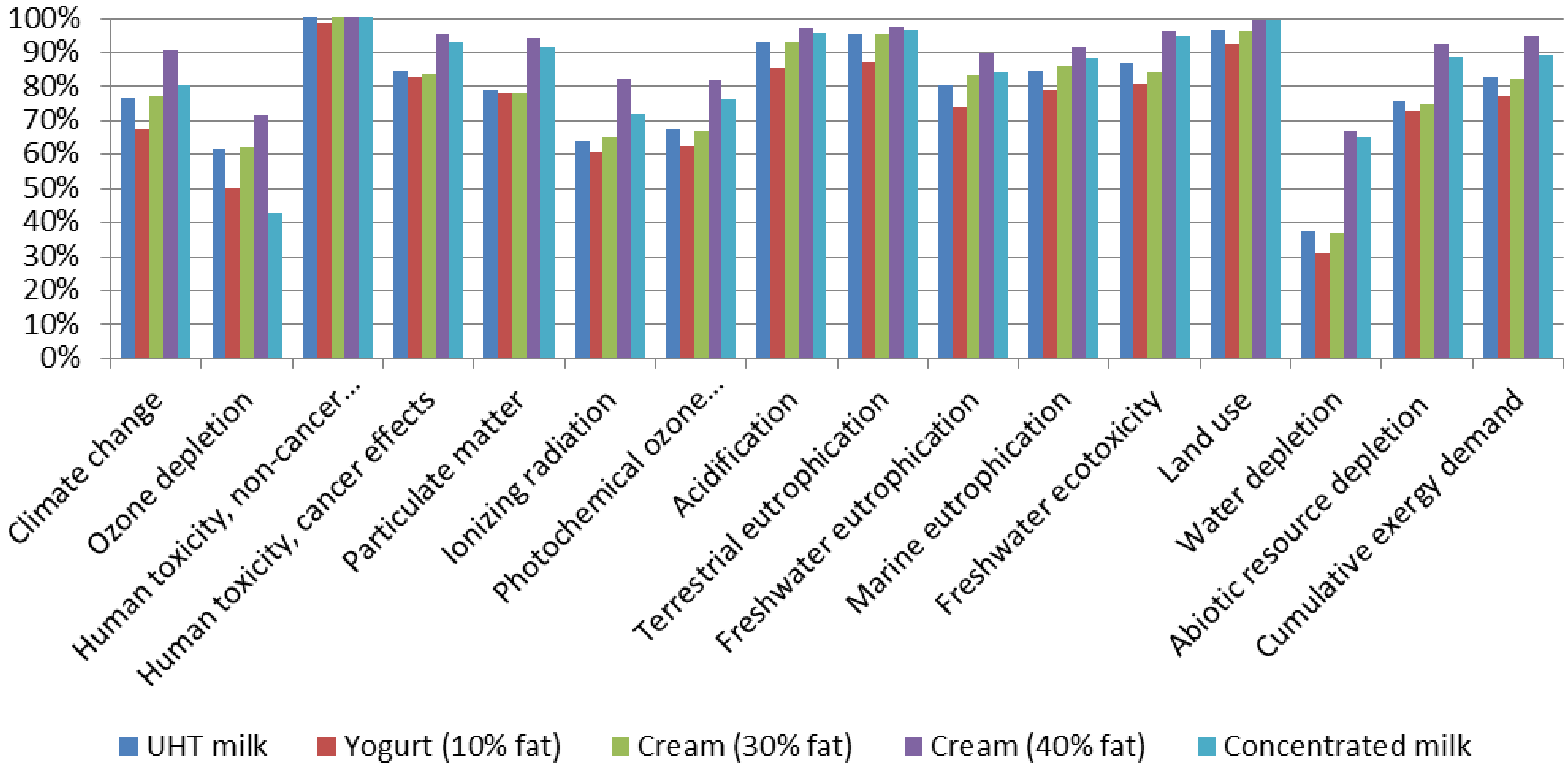

Figure 8 ILDC impact categories: Share of raw milk production at farm of total impact per kilogram of dairy product.

4.2.4.2. *Climate change impacts for single products*

In Figure 9, the contributions of raw milk production and of the operation on climate change are shown in grey and correspond to the left axis. The impacts of operation (incl. raw milk transport) is depicted in more details in colors and correspond to the right axis.

As for all other categories as well, the main impact of dairy products on climate change stems from the raw milk production. The products with the highest fat content have the highest impact (see Figure 9). The concentrated milk has lower impacts than the cream due to the allocation choice of the raw milk separation step, which is conducted according to the dry mass content.

When the process stages of the impact excluding raw milk production are analyzed, it comes clear that the shares of impact are very different for the five considered dairy products. The importance of each process stage changes depending on the processing conducted. For impact on climate change of concentrated milk, the steam (i.e. heat) use has the biggest share. For cream packaged in Tetra Brik of a quarter liter size, the packaging (material production and waste treatment) has the highest effect. For yogurt production, the milk powder has an important share even though the respective input is less than 2% of the total yogurt weight.

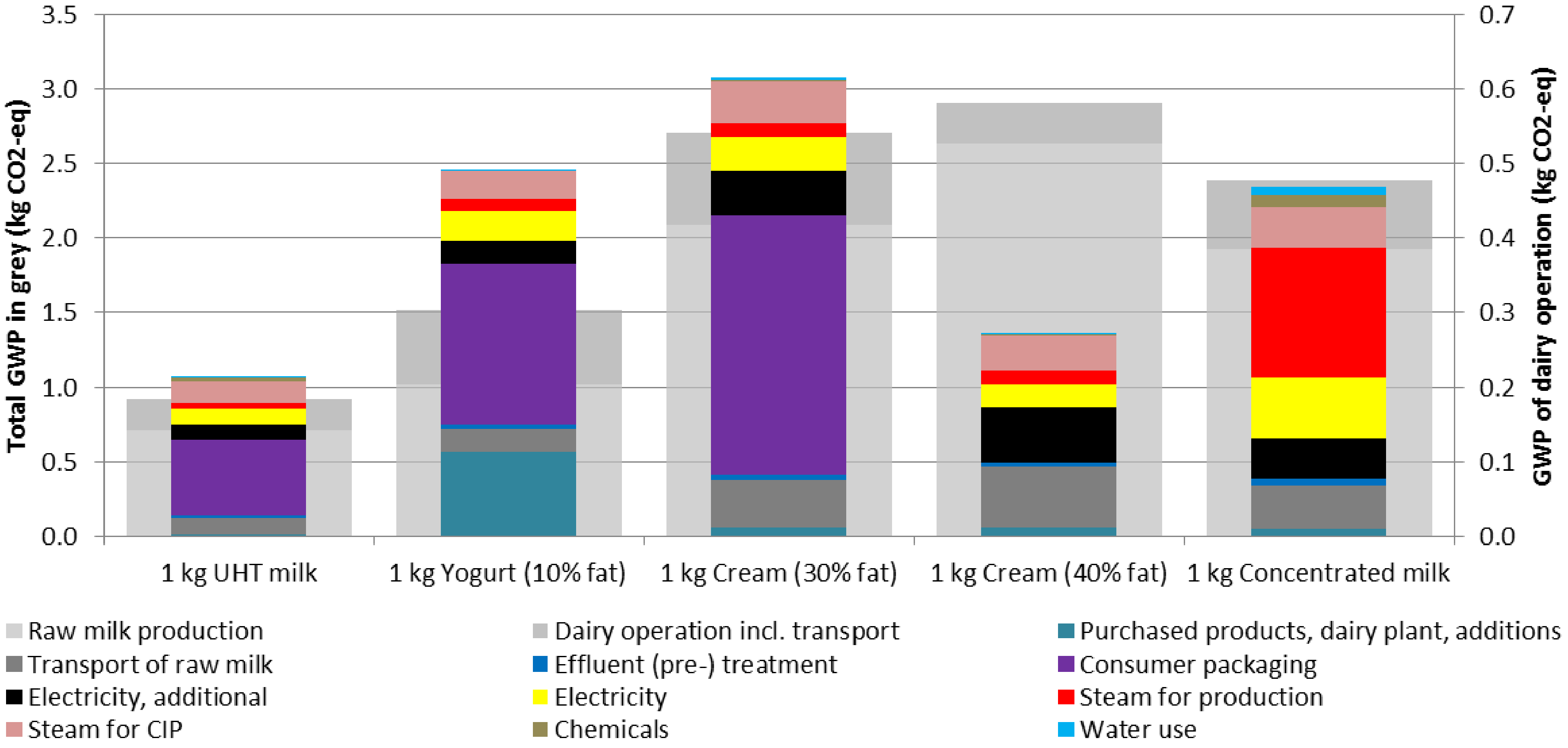

Figure 9 Comparison of global warming potential of different milk products at dairy gate. The columns in the back show the total GWP (left axis) split into raw milk production (light grey) and dairy operation (dark grey). The colored columns show the subdivision of the dairy operation in groups (right axis, groups defined above in "analysis of groups"). All groups above the black group stem from the generic dairy model, all from the black bar to the bottom stem from the additional inputs included in the LCA dairy model.

4.3. Heat supply

In this chapter, different options for the heat supply in the dairy are compared and analyzed. The following questions are answered in this chapter:

- Which influence on the environmental impacts can be expected by implementing state of the art and new technologies developed in the SUSMILK project in existing European dairies instead of the heat supply from an natural gas boiler as assumed in the generic dairy? (Chapter 4.3.1)
- Which factors are relevant for the cause of environmental impacts? (Chapter 4.3.2)
- Where shall technology partners put their focus on in order to improve the technology options? (Chapters 4.3.5, 4.3.6, 4.3.7, 4.3.8)

4.3.1. Comparison of heating options

The thermal output needed for the generic dairy is about 6’000 kW (Assuming 20 h operation per day). Alternative technologies have been chosen with a size that is closest to the needed heat demand. The following options are compared in this section:

- Conventional technologies
    - three conventional boilers (heat from natural gas boiler, diesel boiler and light fuel oil boiler)
- Improvement options
    - three cogeneration units (two with natural gas and one with wood chips)
    - technologies developed or tested within the SUSMILK framework
        - heat from a small solar-thermal system in connection with a pellet boiler, all installed in Spain
          → small solar-thermal system installed at Queizuar
          → pellet boiler installed at Queizuar
          → combination of the two systems above to a solar-pellet system (10.8% of heat is delivered by the solar system)
          → additional scenario for the pellet boiler including a particle separator (70% reduction of particles)
        - a natural gas driven heat pump that uses waste heat
    - three additional scenarios for solar collectors (solar-thermal system on roof, large solar-thermal system on open ground and on flat roof)

A description of the investigated heat supply processes is provided in Table 12. All processed do not take into account the energy loss from heat to steam used at the processes, which is estimated in the generic dairy with 84%.

A natural gas boiler is the heat source used in the generic dairy model (see Table 12, line 1) and serves as a reference value for comparison with the improvement options and generic data. The results for the impact categories recommended by the ILCD are depicted first, followed by the results for the cumulative exergy demand.

Table 12 Overview and description of the heating processes which are compared and analyzed, efficiencies related to LHV of the fuel

Short name	Exact name of process (LINK)	Source	Power (kW)	Comment
Natural gas boiler	heat, natural gas, at industrial furnace >100kW/RER	ecoinvent v2.2 (Schori et al. 2012)	>100 (thermal)	Natural gas boiler. 95% efficiency from gas to heat. Reference for generic dairy
Diesel boiler	diesel, burned in diesel boiler	This study	200	Diesel boiler with 95% efficiency. Some emissions measured at Queizuar.
Light fuel oil boiler	heat, light fuel oil, at industrial furnace 1MW/RER	ecoinvent v2.2 (Jungbluth 2007)	1’000 (thermal)	Old technology that is still used in many dairies. 95% efficiency from oil to heat.
Cogen. (motor), natural gas	heat, at cogen 1MWe lean burn, allocation exergy/CH	ecoinvent v2.2 (Schori et al. 2012)	1’000 (electric)	Improvement option with generic data: 1MW electric with 38% electric, 44% heat. (Heck 2007, Table. 3.1).
Cogen. (turbine), natural gas	heat, natural gas, at turbine, 10MW, allocation exergy /GLO	ecoinvent v2.2 (Faist Emmenegger et al. 2007)	10’000 (electric)	Improvement option. Own assumption 11% electric, 67% heat, with 0.11 MJ-eq exergy content per MJ heat output
Cogen., wood	heat, at cogen 6400kWth, wood, emission control, allocation exergy/ RER	ecoinvent v2.2 (Bauer 2007)	6’400 (thermal)	Improvement option. Large CHP for wood to be installed at the dairy. 8.3% electric efficiency, 80% heat with 0.335 MJ-eq exergy content per MJ heat output
Pellet boiler	heat, wood pellets, at boiler 70kW/RER	This study	70 (thermal)	Improvement option developed in the project, efficiency of 94.3%
Small solar system (ES)	heat, solar system, 56m2 CPC solar thermal collector, on flat roof, at dairy Queizuar/ES	This study	3 (thermal)	Improvement option used at a small dairy in Spain
Large solar system (DE), on roof	heat, solar system, 4'000m2 SUNeco solar thermal collector, on flat roof/RER	This study	200 (thermal, average)	Improvement option with 4’000 m2 aperture area installed on flat roof of the generic dairy
Large solar system (DE), on open ground	heat, solar system, 10'000m2 SUNeco solar thermal collector, open ground installation/RER	This study	500 (thermal, average)	Improvement option with 10’000 m2 aperture area installed on open-ground
Solar-pellet-system (ES)	heat, dairy Queizuar, at solar-pellet-system/ES	This study	2 (thermal, average)	Improvement option, calculated with a solar ratio of 10.8%[10].
Gas-engine driven heat pump	heat, at gas-engine driven heat pump, 200kW/RER	This study	200 (thermal, average)	Improvement option. Mechanical efficiency of gas engine is 35.45%. Coefficient of performance for 60°C input & 90°C output temperature is 2.69.

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[10] A solar ratio is the share of the yearly heat demand of a solar-pellet system that is provided by solar energy. It is calculated as follows: Solar ratio = 1- (Additional heat, including losses from heat buffer tank)/(Sum of total heat need). E-mail, 4.11.2015, from Joachim Kalkgruber, SOLARFOCUS.

ILCD results and general statements on results of different categories

Figure 10 shows the comparison of impact assessment results in different categories as a percentage in relation to the reference value. These relative results are also shown in Table 13. The absolute values are given in Table 14.

All improvement options have an advantage in the impact categories climate change and ozone depletion in comparison to the reference value (natural gas boiler). For the impact on climate change, a substantial reduction is possible by replacing a natural gas boiler. A reduction to less than 15% of the original impact is possible for the options that do not use natural gas. For the gas-engine driven heat pump and cogeneration with natural gas (motor), a reduction to almost one third is possible. For cogeneration with natural gas (turbine), the reduction is less than half. The heat at the solar systems without backup system cannot fully replace the natural gas boiler; therefore a reduction to less than 10% of the original impact cannot directly be implemented. Furthermore, the small solar system is modelled based on an installation in Spain and the results cannot directly be transferred to the situation in Oberhausen, Germany.

The heat pump and the cogeneration with natural gas (motor) show a reduction in all categories compared to heat from a natural gas boiler (except abiotic resource depletion for the heat pump, where the result of the heat pump is in the same range). If waste heat is available at 60°C and if heat demand of the dairy could be met with water at 90°C, the replacement of the natural gas boiler with the natural-gas driven heat pump could cut the environmental impact at least in half for most categories. For the replacement of the natural gas boiler with a cogeneration system with natural gas, the reduction varies more, but on average also leads to a reduction of 50%. The cogeneration with natural gas (turbine) shows an increase in four impact categories (Photochemical ozone formation, acidification, terrestrial eutrophication and marine eutrophication) and a decrease in the other categories.

For human toxicity, the reference scenario is better than all options except the heat pump and the cogeneration with natural gas (turbine and motor) and except for cogeneration with wood, where human toxicity, cancer effects also performs better.

For particulate matter, heat from the light fuel oil and diesel boiler and all systems that include the burning of pellets (cogeneration with wood, pellet boiler, solar-pellet-system) have extremely higher environmental burdens compared to the reference value. The results of the solar system are a bit higher or lower than the reference.

In the impact categories freshwater eutrophication and freshwater ecotoxicity, the cogeneration with natural gas and the gas-engine driven heat pump show lower results, whereas all other options show higher results, mainly extremely higher. The results of the cogeneration with wood behave similar to the ones of cogeneration with natural gas in these two categories, except for freshwater ecotoxicity, where the wood-driven cogeneration shows extremely higher results.

Many impact categories show similar results since the same emissions (see e.g. emission of nitrogen oxides to air) are responsible for various environmental problems.

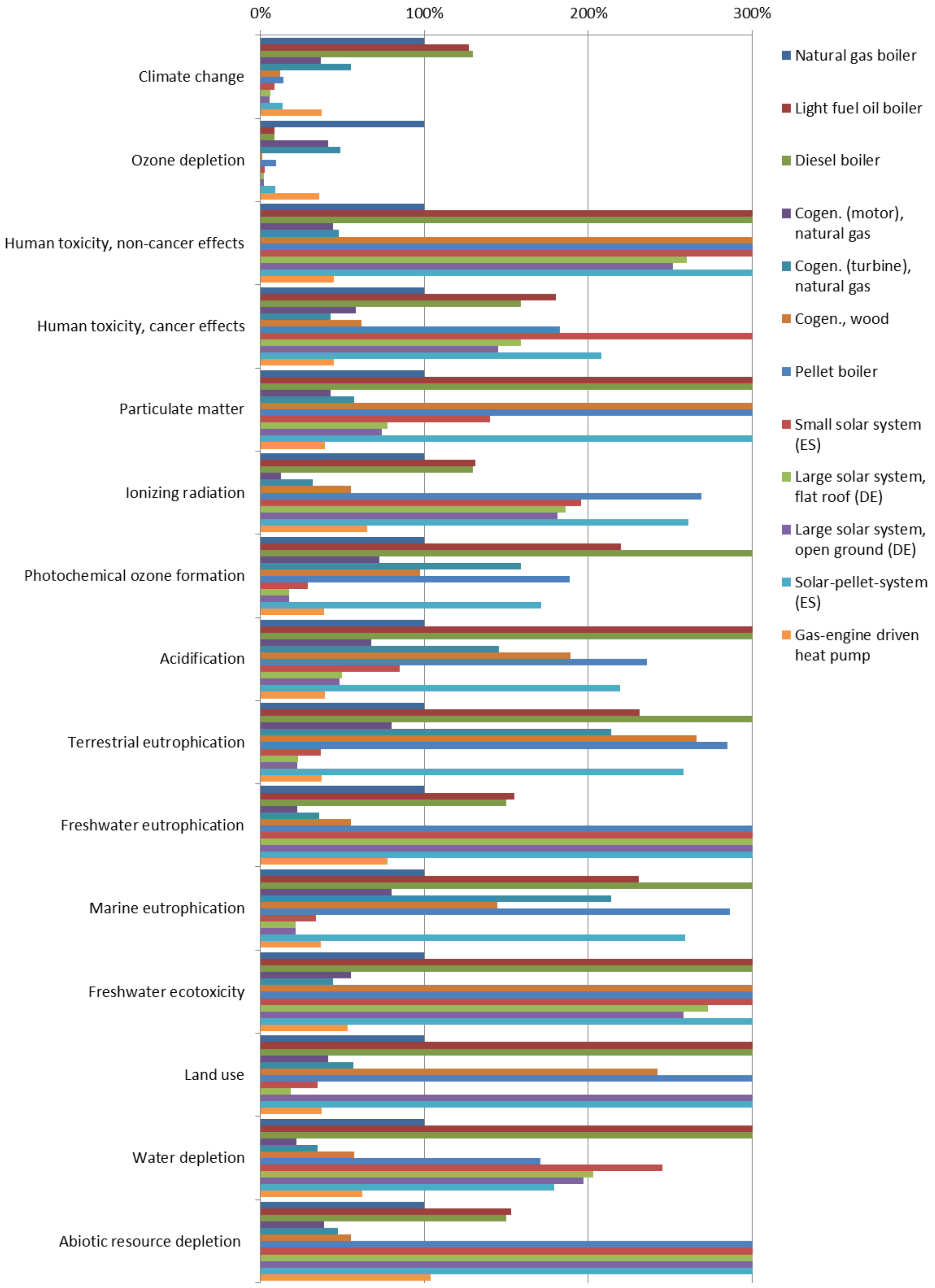

Figure 10 ILDC impact categories: Comparison of heat supply options, given in percentage of the reference scenario (heat from burning natural gas in a boiler, always 100%, not shown). Formula used: (Value of option / Reference value). If the environmental impact of the considered option is more than three times higher than the reference scenario, the value is not shown. Please refer to the table below.

Table 13 ILDC impact categories: Comparison of heat supply options, given in percentage of the reference scenario (heat from burning natural gas in a boiler, always 100%, not shown). Formula used: (Value of option / Reference value). Increases are in red and lightly shaded, reductions are in green and without shade. The darker the color, the further away is the result from the reference value.

Impact category	Light fuel oil boiler	Diesel boiler	Cogen. (motor), natural gas	Cogen. (turbine), natural gas	Cogen., wood	Pellet boiler	Pellet boiler with particle separator	Small solar system (ES)	Large solar system, flat roof (DE)	Large solar system, open ground (DE)	Solar-pellet-system (ES)	Gas-engine driven heat pump
Climate change	127%	129%	37%	55%	**12%**	**14%**	**14%**	**8%**	**6%**	**6%**	**13%**	37%
Ozone depletion	**9%**	**9%**	41%	49%	**1%**	**9%**	**9%**	**3%**	**2%**	**2%**	**9%**	36%
Human toxicity, non-cancer effects	**2592%**	**385%**	44%	48%	**1072%**	**1064%**	**1064%**	**492%**	**260%**	**252%**	**1002%**	45%
Human toxicity, cancer effects	180%	159%	58%	43%	62%	183%	184%	**414%**	159%	145%	**208%**	45%
Particulate matter	**559%**	**600%**	43%	57%	**682%**	**2082%**	**889%**	140%	78%	74%	**1871%**	39%
Ionizing radiation	131%	130%	**13%**	32%	55%	**269%**	**270%**	195%	186%	181%	**261%**	65%
Photochemical ozone formation	**220%**	**360%**	73%	159%	97%	189%	189%	29%	**18%**	**17%**	171%	39%
Acidification	**514%**	**485%**	67%	145%	189%	**236%**	**236%**	85%	50%	48%	**220%**	39%
Terrestrial eutrophication	**232%**	**333%**	80%	**214%**	**266%**	**285%**	**285%**	37%	**23%**	**23%**	**258%**	37%
Freshwater eutrophication	155%	150%	**22%**	36%	55%	**431%**	**432%**	**1443%**	**548%**	**529%**	**542%**	78%
Marine eutrophication	**231%**	**326%**	80%	**214%**	145%	**287%**	**287%**	34%	**21%**	**21%**	**259%**	37%
Freshwater ecotoxicity	**2750%**	**729%**	55%	44%	**487%**	**878%**	**880%**	**592%**	**273%**	**258%**	**848%**	53%
Land use	**695%**	**702%**	41%	57%	**243%**	**1235%**	**1235%**	35%	**18%**	**2072%**	**1105%**	37%
Water depletion	**424%**	**424%**	**22%**	35%	57%	171%	171%	**246%**	**203%**	197%	179%	62%
Abiotic resource depletion	153%	150%	39%	47%	55%	**1638%**	**1640%**	**1499%**	**627%**	**610%**	**1632%**	104%

Table 14 ILDC impact categories: Comparison of heat supply options given in absolute values per MJ of delivered heat

Impact category		Natural gas boiler	Light fuel oil boiler	Diesel boiler	Cogen. (motor), natural gas	Cogen. (turbine), natural gas	Cogen., wood	Pellet boiler	Pellet boiler with particle separator	Small solar system (ES)	Large solar system, flat roof (DE)	Large solar system, open ground (DE)	Solar-pellet-system (ES)	Gas-engine driven heat pump
Climate change	kg CO2 eq	7.1E-02	9.1E-02	9.2E-02	2.6E-02	3.9E-02	8.5E-03	9.9E-03	9.9E-03	6.0E-03	4.2E-03	4.0E-03	9.4E-03	2.7E-02
Ozone depletion	kg CFC-11 eq	8.9E-09	7.7E-10	7.7E-10	3.7E-09	4.4E-09	8.3E-11	8.4E-10	8.4E-10	2.4E-10	1.9E-10	1.8E-10	7.9E-10	3.2E-09
Human toxicity, non-cancer effects	CTUh	4.9E-10	1.3E-08	1.9E-09	2.2E-10	2.3E-10	5.3E-09	5.2E-09	5.2E-09	2.4E-09	1.3E-09	1.2E-09	4.9E-09	2.2E-10
Human toxicity, cancer effects	CTUh	9.3E-11	1.7E-10	1.5E-10	5.4E-11	4.0E-11	5.7E-11	1.7E-10	1.7E-10	3.9E-10	1.5E-10	1.4E-10	1.9E-10	4.2E-11
Particulate matter	kg PM2.5 eq	2.8E-06	1.6E-05	1.7E-05	1.2E-06	1.6E-06	1.9E-05	5.9E-05	2.5E-05	4.0E-06	2.2E-06	2.1E-06	5.3E-05	1.1E-06
Ionizing radiation	kBq U235 eq	3.6E-04	4.8E-04	4.7E-04	4.6E-05	1.2E-04	2.0E-04	9.8E-04	9.8E-04	7.1E-04	6.8E-04	6.6E-04	9.5E-04	2.4E-04
Photochemical ozone formation	kg NMVOC eq	6.3E-05	1.4E-04	2.2E-04	4.5E-05	1.0E-04	6.1E-05	1.2E-04	1.2E-04	1.8E-05	1.1E-05	1.1E-05	1.1E-04	2.4E-05
Acidification	molc H+ eq	5.3E-05	2.7E-04	2.6E-04	3.6E-05	7.7E-05	1.0E-04	1.2E-04	1.2E-04	4.5E-05	2.6E-05	2.5E-05	1.2E-04	2.1E-05
Terrestrial eutrophication	molc N eq	1.7E-04	4.1E-04	5.8E-04	1.4E-04	3.7E-04	4.7E-04	5.0E-04	5.0E-04	6.4E-05	4.0E-05	4.0E-05	4.5E-04	6.5E-05
Freshwater eutrophication	kg P eq	1.6E-07	2.5E-07	2.4E-07	3.6E-08	5.8E-08	8.8E-08	6.9E-07	6.9E-07	2.3E-06	8.8E-07	8.5E-07	8.7E-07	1.2E-07
Marine eutrophication	kg N eq	1.6E-05	3.7E-05	5.2E-05	1.3E-05	3.4E-05	2.3E-05	4.6E-05	4.6E-05	5.4E-06	3.4E-06	3.4E-06	4.1E-05	5.9E-06
Freshwater ecotoxicity	CTUe	1.4E-03	3.8E-02	1.0E-02	7.6E-04	6.1E-04	6.7E-03	1.2E-02	1.2E-02	8.2E-03	3.8E-03	3.6E-03	1.2E-02	7.4E-04
Land use	kg C deficit	1.9E-02	1.3E-01	1.3E-01	7.6E-03	1.1E-02	4.5E-02	2.3E-01	2.3E-01	6.5E-03	3.4E-03	3.9E-01	2.1E-01	6.9E-03
Water depletion	m3 water eq	9.9E-06	4.2E-05	4.2E-05	2.2E-06	3.4E-06	5.6E-06	1.7E-05	1.7E-05	2.4E-05	2.0E-05	1.9E-05	1.8E-05	6.1E-06
Abiotic resource depletion	kg Sb eq	2.2E-08	3.4E-08	3.3E-08	8.6E-09	1.0E-08	1.2E-08	3.6E-07	3.6E-07	3.3E-07	1.4E-07	1.3E-07	3.6E-07	2.3E-08

Cumulative Exergy demand and general statements on results of different categories

Figure 11 shows the comparison of the cumulative exergy demand of different systems providing heat. The cumulative exergy demand is split into different subcategories. It is visible that the cumulative exergy demand systems using wood do not use less exergy, but the exergy stems from a renewable source (biomass) and not from fossil exergy. For all options that use wood or solar irradiation as energy source, the highest share of the cumulative exergy demand stems from renewable sources. For options that use natural gas, diesel or light fuel oil, the highest share stems from non-renewable sources. The absolute values used in the figure are given in Table 16.

The exergy content of hot water in the solar collectors has been taken into account, thus calculating the cumulative exergy content more adequately than in the method of Bösch et al. For details, please refer to Chapter 3.2.7.6. Thus, only the exergy lost within the solar system is depicted, revealing the advantage of solar collectors in the cumulative exergy demand. The cogeneration of heat and electricity with natural gas needs less exergy for the heat, since the exergy of natural gas is used more efficiently and since part of the exergy input is used to produce electricity. The gas engine driven heat pump that uses waste heat also leads to good results. All improvement options (i.e. all options excluding the light fuel oil boiler) lead to better results in the cumulative exergy demand if only non-renewable sources of exergy are considered.

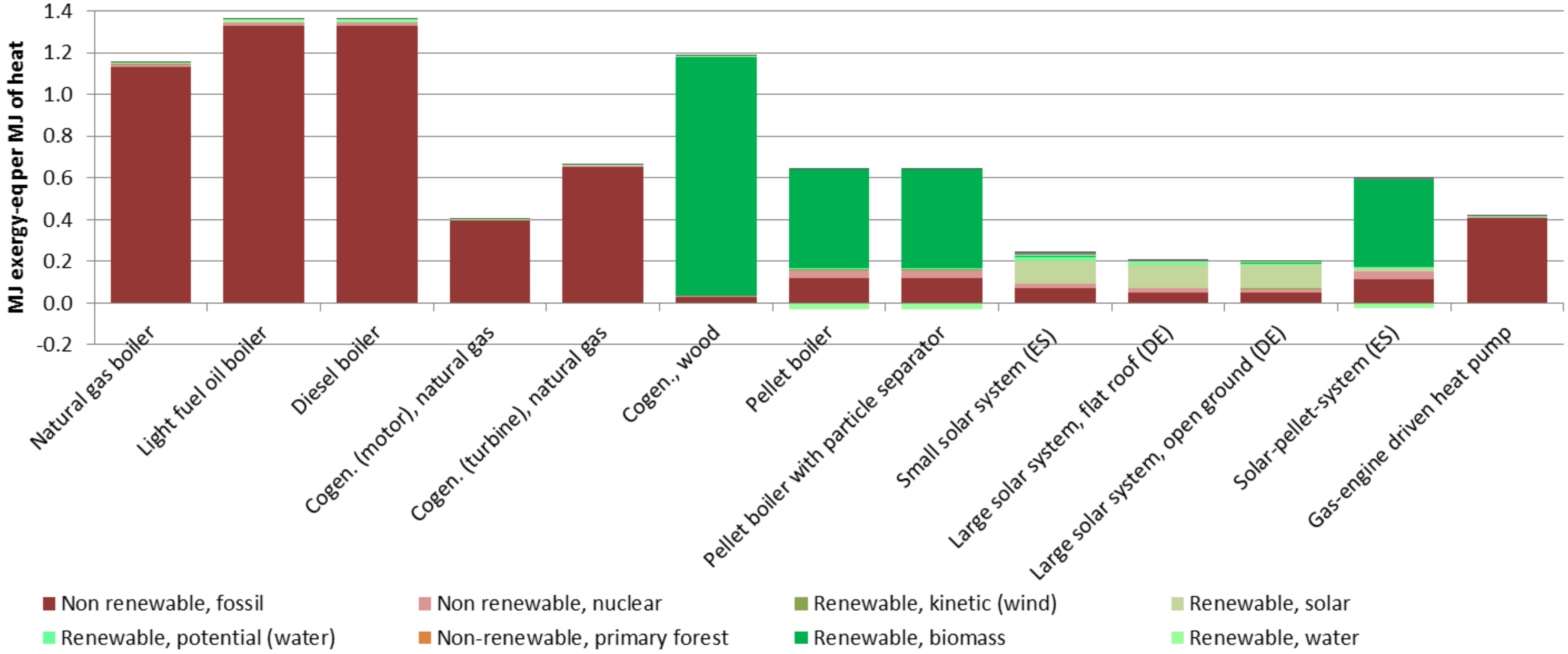

Figure 11 Cumulative exergy demand in MJ-eq per MJ of heat delivered. Non-renewable exergy inputs are depicted in red and grey (grey for minerals and metals), renewable exergy is depicted in green. For the solar systems, the exergy content of 0.12 of hot water at the used temperature in the collector is used.

In Table 15, relative results are given: The cumulative exergy demand of different heating systems in each sub-category is divided by the sum of the cumulative exergy demand of the natural gas boiler (reference scenario). All results in this table are therefore referenced to the total exergy demand of the reference scenario.

In the sub-category non-renewable, fossil, all improvement options (all options except the light fuel oil and diesel boiler) are better compared to the reference that is heat from burning natural gas in a boiler. The options using wood energy need more exergy than the reference in the sub-category renewable, biomass (see values in bold). For the cogeneration with wood, the increase in this sub-category is comparable to the decrease in the sub-category non-renewable, fossil and the total exergy demand is in the same range as the reference. For the pellet boiler and the solar-pellet-system, The increase in the sub-category renewable, biomass is smaller than the decrease in the sub-category non-renewable, fossil. This leads to a total exergy decrease of about 50% compared to the reference.

Table 15 Comparison of the cumulative exergy demand of heat supply options, given in percentage of the cumulative exergy demand of the reference scenario (heat from burning natural gas in a boiler). Formula used: (Value of option / Cumulative exergy demand of reference). Increases are in red and lightly shaded, reductions are in green and without shade. The darker the color, the further away is the result from the reference value.

Impact category	Natural gas boiler	Light fuel oil boiler	Diesel boiler	Cogen. (motor), natural gas	Cogen. (turbine), natural gas	Cogen., wood	Pellet boiler	Pellet boiler with particle separator	Small solar system (ES)	Large solar system, flat roof (DE)	Large solar system, open ground (DE)	Solar-pellet-system (ES)	Gas-engine driven heat pump
Non renewable, fossil	98.33%	115.19%	115.47%	34.38%	56.77%	**2.52%**	**10.39%**	**10.41%**	**6.09%**	**4.35%**	**4.22%**	**9.94%**	35.32%
Non renewable, nuclear	0.95%	1.24%	1.22%	0.12%	0.30%	0.52%	3.33%	3.34%	1.94%	1.79%	1.74%	3.18%	0.62%
Renewable, kinetic (wind)	0.04%	0.05%	0.05%	0.00%	0.01%	0.02%	0.18%	0.18%	0.06%	0.07%	0.07%	0.17%	0.03%
Renewable, solar	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	**9.84%**	**9.84%**	**9.84%**	1.07%	0.00%
Renewable, potential (water)	0.29%	0.24%	0.24%	0.06%	0.13%	0.10%	0.71%	0.72%	1.14%	0.61%	0.55%	0.76%	0.16%
Non-renewable, primary forest	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Renewable, biomass	0.06%	0.08%	0.08%	0.01%	0.02%	**99.24%**	**40.94%**	**40.94%**	0.30%	0.22%	0.22%	**36.54%**	0.04%
Renewable, water	0.26%	1.12%	1.12%	0.06%	0.09%	0.15%	-2.55%	-2.54%	0.65%	0.54%	0.52%	-2.20%	0.16%
Non renewable, metals	0.04%	0.07%	0.07%	0.03%	0.02%	0.03%	0.14%	0.14%	0.81%	0.28%	0.26%	0.21%	0.04%
Non renewable, minerals	0.02%	0.03%	0.03%	0.01%	0.01%	0.02%	0.03%	0.03%	0.01%	0.01%	0.01%	0.03%	0.01%
Cumulative exergy demand	100.00%	118.01%	118.28%	34.68%	57.36%	102.60%	53.20%	53.22%	**20.84%**	**17.71%**	**17.43%**	49.71%	36.38%

Table 16 Cumulative exergy demand of heat supply options given in absolute values (MJ-eq cumulative exergy demand per MJ of heat supplied). The relevant sub-categories of each process are shaded. (The value of each sub-categories is compared to all other sub-categories within each process (i.e. heat, natural gas boiler). Higher values are shaded darker.)

Impact category		Natural gas boiler	Light fuel oil boiler	Diesel boiler	Cogen. (motor), natural gas	Cogen. (turbine), natural gas	Cogen., wood	Pellet boiler	Pellet boiler with particle separator	Small solar system (ES)	Large solar system, flat roof (DE)	Large solar system, open ground (DE)	Solar-pellet-system (ES)	Gas-engine driven heat pump
Non renewable, fossil	MJ	1.1E+00	1.3E+00	1.3E+00	4.0E-01	6.5E-01	2.9E-02	1.2E-01	1.2E-01	7.0E-02	5.0E-02	4.9E-02	1.1E-01	4.1E-01
Non renewable, nuclear	MJ	1.1E-02	1.4E-02	1.4E-02	1.4E-03	3.5E-03	5.9E-03	3.8E-02	3.8E-02	2.2E-02	2.1E-02	2.0E-02	3.7E-02	7.2E-03
Renewable, kinetic (wind)	MJ	4.9E-04	6.1E-04	6.1E-04	5.6E-05	1.6E-04	2.3E-04	2.1E-03	2.1E-03	6.5E-04	7.7E-04	7.6E-04	2.0E-03	3.2E-04
Renewable, solar	MJ	2.4E-05	3.1E-05	3.0E-05	2.6E-06	7.6E-06	1.2E-05	1.9E-05	2.0E-05	1.1E-01	1.1E-01	1.1E-01	1.2E-02	4.0E-05
Renewable, potential (water)	MJ	3.4E-03	2.7E-03	2.7E-03	7.0E-04	1.4E-03	1.1E-03	8.2E-03	8.2E-03	1.3E-02	7.0E-03	6.4E-03	8.8E-03	1.8E-03
Non-renewable, primary forest	MJ	9.7E-07	1.7E-06	1.7E-06	5.8E-07	4.1E-07	7.4E-08	5.7E-05	5.7E-05	7.1E-07	4.4E-07	4.1E-07	5.1E-05	3.5E-07
Renewable, biomass	MJ	6.8E-04	8.8E-04	9.0E-04	1.4E-04	2.2E-04	1.1E+00	4.7E-01	4.7E-01	3.5E-03	2.5E-03	2.5E-03	4.2E-01	4.4E-04
Renewable, water	MJ	3.0E-03	1.3E-02	1.3E-02	6.8E-04	1.1E-03	1.7E-03	-2.9E-02	-2.9E-02	7.5E-03	6.2E-03	6.0E-03	-2.5E-02	1.9E-03
Non renewable, metals	MJ	5.1E-04	7.7E-04	7.5E-04	3.3E-04	2.4E-04	2.9E-04	1.6E-03	1.6E-03	9.4E-03	3.2E-03	3.0E-03	2.5E-03	4.3E-04
Non renewable, minerals	MJ	1.8E-04	3.8E-04	3.9E-04	1.1E-04	8.1E-05	2.0E-04	3.8E-04	3.8E-04	1.2E-04	1.3E-04	1.5E-04	3.5E-04	6.8E-05
Cumulative exergy demand	*MJ*	***1.15***	***1.36***	***1.36***	***0.40***	***0.66***	***1.18***	***0.61***	***0.61***	***0.24***	***0.20***	***0.20***	***0.57***	***0.42***

4.3.2. Analysis of the comparison of heating options

This chapter further analyses different options in the comparison. Details for single technologies are evaluated in the following chapters.

Climate Change & Ozone depletion

All improvement options show an impact reduction of at least 40% up to to over 90% in the categories climate change and ozone depletion compared to the reference value.

The main emission source for the ozone depletion is the emission of bromochromodifluoro- und chromotrifluoromethane. For most options, this stems from long distance transportation of natural gas in pipelines, so finally from natural gas use. For heat from the light fuel oil boiler and from cogeneration with wood, the emission of bromotrifluoromethane from crude oil production is the decisive input. It is used as fire extinguisher. The emission stems from leakage, losses at fillingand false alarms. Ozone depleting substances are today seldomly used and their use has been phasing out for several decades. Therefore, results are dominated by older background data which does not take into account the most recent reduction. Thus, results are very uncertain and they should not be considered for the decision making.

The main emission source for climate change is carbon dioxide emissions from fossil sources in all options except the heat from cogeneration with wood. There, the main emission source is dinitrogen monoxide that stems directly from the burning of the wood chips in the furnace.

Human toxicity, non-cancer effect

The results from heat from the natural gas driven heat pump and the cogeneration with natural gas (motor and turbine) are more than 50% lower than the reference value. All other scenarios have a considerably higher respectively extremely higher value.

For the systems with only solar collectors, the main emission source leading to the impact is the emission of zinc to air, mainly stemming from copper production. For all the options that supply heat by burning natural gas (reference value, cogeneration with natural gas, heat pump) and for the diesel boiler, the combustion emissions of mercury to air are the crucial values. For heat from the light fuel oil boiler, the main impact stems from zinc emissions to air from the burning of the fuel oil. For heat from burning wood, the main impact stems from zinc emissions to air during the combustion process (cogeneration with wood, pellet boiler, solar-pellet-system)

Human toxicity, cancer effect

The two conventional technologies (light fuel oil and diesel boiler) and all systems including solar technology cause higher to extremely higher impacts compared to the natural gas boiler, whereas the values for the heat pump and the three cogeneration types are lower, partly considerably lower.

The toxicity in the heating comparison originates to the largest part from chromium VI emissions into water in all considered technologies. The unit processes that are responsible emissions with the main impact on human toxicity, cancer effects, are disposal of redmud from bauxite digestion (for the solar systems), wood pellet production including the whole supply chain (for all systems including pellets), and the disposal of slags due to steel production (for the conventional technologies, cogeneration, heat pump) and are therefore dependent on the amount of stainless steel needed.

Particulate matter

The options that include wood combustion and heat from the conventional boilers (light fuel oil, diesel) have extremely higher values compared to the reference (factor of more than five). The three options with natural gas (CHPs and heat pump) have lower values (40 - 60% reduction). The results from the solar systems do not deviate much from the reference (small solar system is a bit higher, the large solar system on roof is a bit lower, the large solar system on open ground is in the same range). The unit processes with the biggest direct emissions are the processes in which the fuels are burned. The exceptions are the solar systems, where the production of aluminum is the process with the biggest direct impact.

The emissions with the highest influence in this category are sulfur dioxide and particulate emissions. For wood based heating systems, the particulate emissions contribute to 90 to 95% of the impacts, whereas sulfur dioxide emissions do not contribute much.

Ionizing radiation

The results of heat from conventional boilers (light fuel oil and diesel) and from the small solar system are only a bit higher than heat from the natural gas boiler. The heat from cogeneration and from the gas-engine driven heat pump is lower (wood) up to extremely lower (with natural gas, motor). All other values are higher to considerably higher (solar systems, pellet boiler, solar-pellet-system).

The impact category ionizing radiation is driven by the reprocessing of nuclear waste and therefore from production of electricity in nuclear power plants. For heat from cogeneration with wood, electricity used for wood chopping is the crucial process. For heat at pellet boiler, the pressing of the pellets is the crucial influence.

Photochemical ozone formation & Acidification

Compared to the reference value, the pellet boiler and the solar-pellet-system at Queizuar have higher (ozone formation) and considerably higher values (acidification), the heat from the conventional boilers even reach considerably (ozone formation) and extremely higher results (acidification). The heat from cogeneration with wood has results in the same range for ozone formation, but higher values for acidification. The cogeneration (turbine) with natural gas has higher results. All other options (cogeneration (motor) with natural gas, all solar systems, heat pump) reach lower to extremely lower values. The results of the large solar system are lower for ozone formation, but comparable to the reference value for acidification.

For the photochemical ozone formation, the emission of nitrogen oxides leads to the main impacts. For the acidification, the emission of nitrogen oxides as well as sulfur dioxide cause the main impact, except for heat from cogeneration with wood, where ammonia has the main emission, followed by nitrogen oxides.

Eutrophication, terrestrial & marine

These results show a very similar pattern to acidification. For both categories, the emission of nitrogen oxides cause the main impact. Again there is an exception for the cogeneration with wood, where ammonia emissions to air cause half the impact in the impact category terrestrial eutrophication.

Eutrophication, freshwater

The results of the heat from the heat pump are a bit lower, for cogeneration from wood lower. For cogeneration with natural gas, the results are considerably lower (turbine CHP) and extremely lower (motor CHP). The results for heat from the conventional boilers are higher, while all other options (all solar systems, pellet boiler, solar-pellet-system) cause extremely high emissions (more than a factor of 5).

The emission of phosphate to water contributes the major part to the freshwater eutrophication.

Freshwater ecotoxicity

The heat pump and the cogeneration with natural gas (motor and turbine) show lower impacts (about half). All other results are considerably to extremely higher than the reference value (factor of almost 3 to 27), highest for heat from the light fuel oil boiler.

The emissions of chromium to water contribute most to the impact for all options with natural gas (reference value, both cogenerations with natural gas and the heat pump) and all solar systems. For heat from the light fuel oil boiler, the emission of copper to air contributes most. For the pellet boiler, the solar-pellet-system and the diesel boiler, zinc emissions to air are crucial.

Land use

The results present a similar pattern as for acidification, but show a lower range of values. An exception is the large solar system, where the result for acidification is lower than the reference value, whereas for land use it is extremely higher (factor 20). Also the result for cogeneration with natural gas (turbine) is higher for acidification, whereas it is lower for land use.

The transformation of land to mineral extraction site (options with fossil fuels and the small solar system) respectively the occupation by forest (options with wood, including the solar-pellet-system) contribute most to the potential impact. For the large solar system, the transformation of land to industrial area to mount the solar collectors is the crucial resource use.

Water depletion

The value of the cogeneration with natural gas is extremely (motor) and considerably (turbine) lower compared to natural gas boiler, whereas the values of the cogeneration with wood and of the heat pump are just lower.

All other options are higher (solar-pellet-system, pellet boiler) considerably higher (all solar system) than the reference or extremely higher (conventional boilers). The main contribution to the final result is water used for cooling. Often the cooling is in the context of electricity production. For the light fuel oil boiler, the water use in the refinery is the main impact. For the cogeneration with natural gas, water uses from different inputs that are needed for the natural gas provision are the main factor.

Abiotic resource depletion

The heat pump has comparable results to the reference whereas the three cogeneration options have lower (wood) respectively considerably lower results (natural gas, motor and turbine). The conventional boilers have higher results. The pellet boilers and the solar systems (with and without pellets) show extremely higher values (factor of 6 to 16).

The largest contribution to the result is natural gas for all options using this as the energy source and crude oil for both the light fuel oil and the diesel boiler. For cogeneration with wood, nickel, uranium and lead are the main contributors. For the systems based on solar energy, the use of copper and for the solar collectors with SUNeco collectors also zinc for the powder coating of the steel collector tray are the main resource uses.

For the pellet boiler and the solar-pellet-system, the resource indium has the main impact. Indium appears in zinc mining as a resource input from nature. In the ecoinvent dataset it is assumed that this indium is not used and thus the resource is wasted. But, with a rising demand it would be possible to extract this resource in the process of lead-zinc mining. The indium accounts for about 60% of the total impact, which is also seen as a questionable result of the characterization approach used in the ILCD recommendations. But even if this 60% were subtracted from the impact, the results would still be considerably higher than the reference.

Cumulative exergy demand

The results of the cumulative exergy demand of the solar systems are extremely lower compared to the reference. For the heat from the solar-pellet-system, the heat pump and the cogeneration with natural gas (motor) the values are considerably lower than the reference (natural gas boiler) and lower for cogeneration with natural gas (turbine). The results of the cogeneration with wood and the conventional boilers (light fuel oil, diesel) are in the same range or a bit higher.

Only in the sub-categories renewable, biomass and non-renewable, fossil and renewable, solar, there are results that are more than 5% of the cumulative exergy demand of the reference (bold values in Table 15).

In the sub-category non-renewable, fossil, heat from light fuel oil and diesel boiler are a bit higher, whereas all other options show a decrease in that category. In the category renewable, biomass, all options using wood show an increase, whereas the other do not show big changes.

All systems that only use solar energy need about 10% compared to the cumulative exergy demand of the natural gas boiler as input in the sub-category renewable, solar, whereas the exergy demand of this sub-category for the natural gas boiler is negligible.

4.3.3. Heat from natural gas boiler

The reference of the heating options is heat from an industrial natural gas boiler. The analysis with ILCD methods (see Figure 12) shows that for climate change, the emissions of the burning process contribute most, whereas for all other categories, the provision of natural gas has the highest share. Electricity contributes little in most categories, but in the categories ionizing radiation, freshwater eutrophication and water depletion more than a third to the total impact.

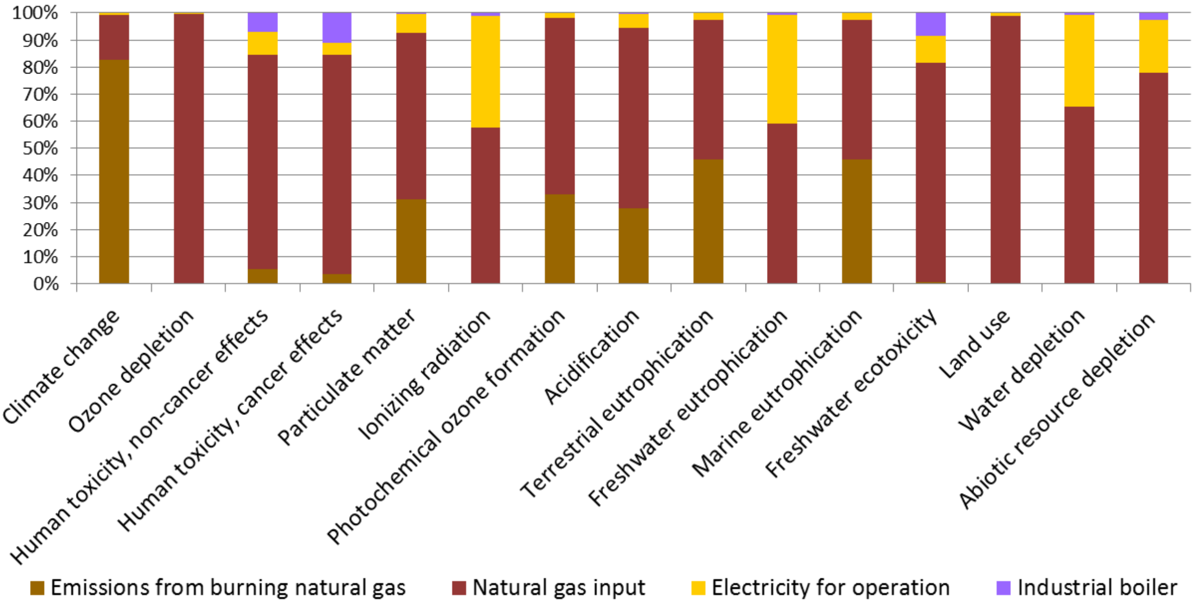

Figure 12 ILCD: Main contributors to the environmental impacts of heat, natural gas, burned in an industrial boiler.

The analysis of the cumulative exergy demand shows that basically all exergy stems from input of natural gas that is assigned to the sub-category non-renewable, fossil (see Figure 12). All other sub-categories of exergy do only contribute very little to the total exergy demand. The share of the electricity and infrastructure are negligible compared to the total.

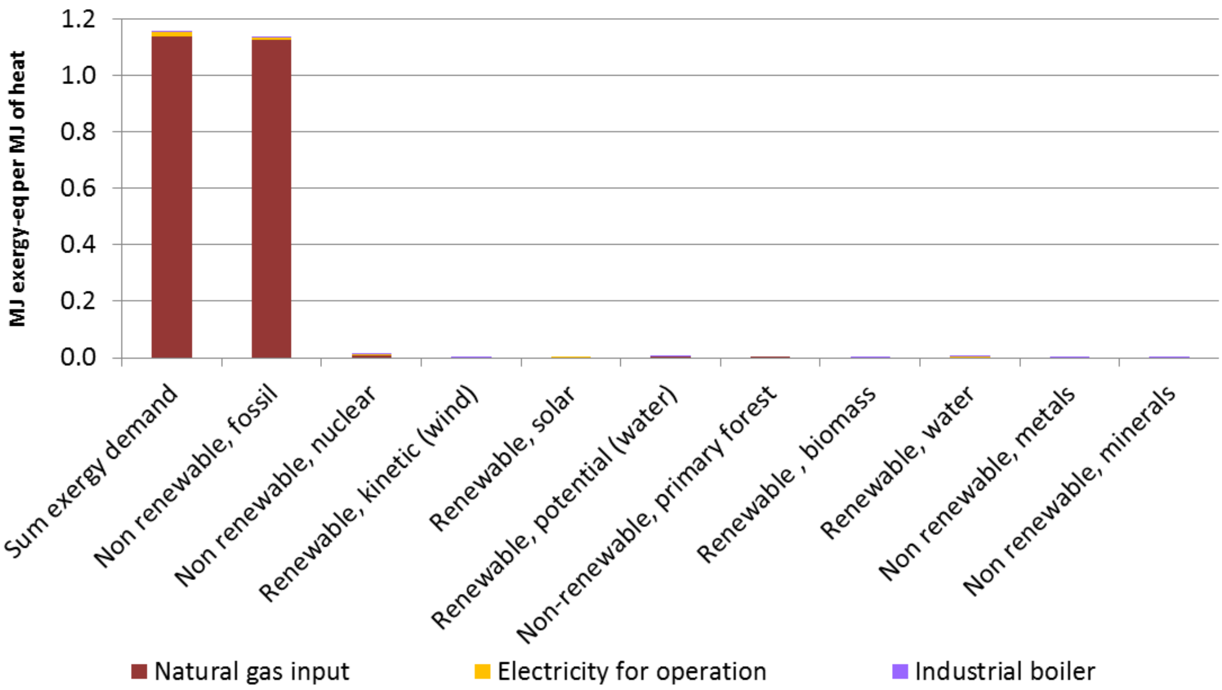

Figure 13 Main contributors to the cumulative exergy demand of heat, natural gas, provided by an industrial boiler. The cumulative exergy demand (left) and its split into sub-categories is shown.

4.3.4. Heat from diesel boiler at Queizuar

The analysis of the diesel boiler shows a similar split (see Figure 14) of the total impact as for natural gas (Figure 12). Also here, the emissions of the burning process contribute most in the impact category climate change. A prominent difference to heat at natural gas boiler is that the emissions from the diesel burning process also contribute most in the impact categories photochemical ozone formation, terrestrial eutrophication and marine eutrophication. For all other categories, the provision of diesel has the highest share. Electricity contributes very little in most categories, and only in the categories ionizing radiation and freshwater eutrophication more than 10 percent. The electricity need for the diesel boiler per MJ of heat provided is smaller than the one of natural gas.

The diesel boiler and the light fuel oil boiler as well have extremely higher impacts on acidification compared to natural gas. The emissions leading to this impact are to a large extent sulfur dioxide emissions. These emissions stem from burning sulfurous natural gas in a production flare in the context of crude oil production.

The results in the impact category freshwater ecotoxicity are also extremely higher, both of the diesel boiler and the light fuel oil boiler. For the diesel boiler, the emission of zinc to air contributes most to the final result. The zinc emission stems to a large extent from the burning process. For the light fuel oil boiler, emissions of copper and zinc to air both contribute to the impact. The emissions stem to a large extent from the burning process.

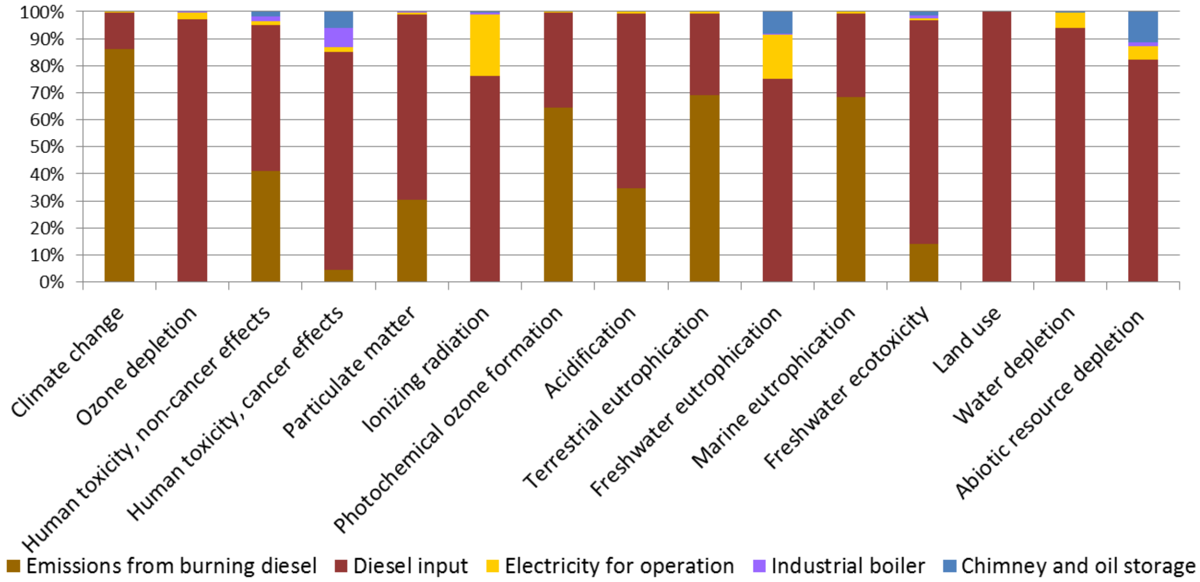

Figure 14 ILCD: Main contributors to the environmental impacts of heat provided by a diesel boiler.

The analysis of the cumulative exergy demand shows that basically all exergy stems from input of diesel that is assigned to the sub-category non-renewable, fossil (see Figure 12). All other sub-categories of exergy do only contribute very little to the total exergy demand. The share of the electricity and infrastructure are negligible compared to the total.

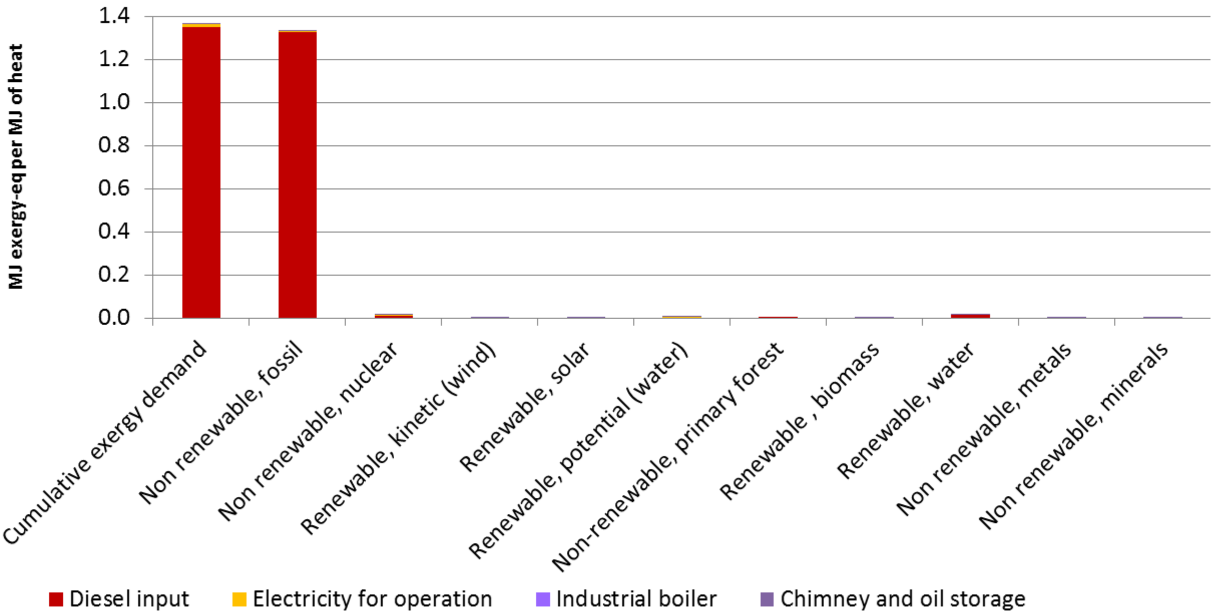

Figure 15 Main contributors to the cumulative exergy demand of heat provided by a diesel boiler. The cumulative exergy demand (left) and its split into sub-categories is shown.

4.3.5. Analysis of heat from small solar collector at Queizuar

The environmental performance of solar collectors is very variable (for details, please refer to Chapter 5.3.5). The heat from solar collector at the dairy Queizuar in Spain is split into the CPC collector (including all inputs for production), the solar system (mounting, piping) and the electricity directly used to operate the solar system.

In almost all impact categories (except for ionizing radiation and cumulative exergy demand), the CPC solar collectors (material, production) contribute most to the total impact. The values range between 40% and 65%. A detailed analysis of the CPC collectors is shown in Figure 18.

The solar system that includes copper pipes connecting the collectors, a mounting system, a pump and a buffer tank has the second highest impact in most categories, while the electricity use to drive the pump only contributes little. The exception is the ionizing radiation, where electricity from nuclear sources is the main source.

Analysis of heat of small solar system at Queizuar: Overview

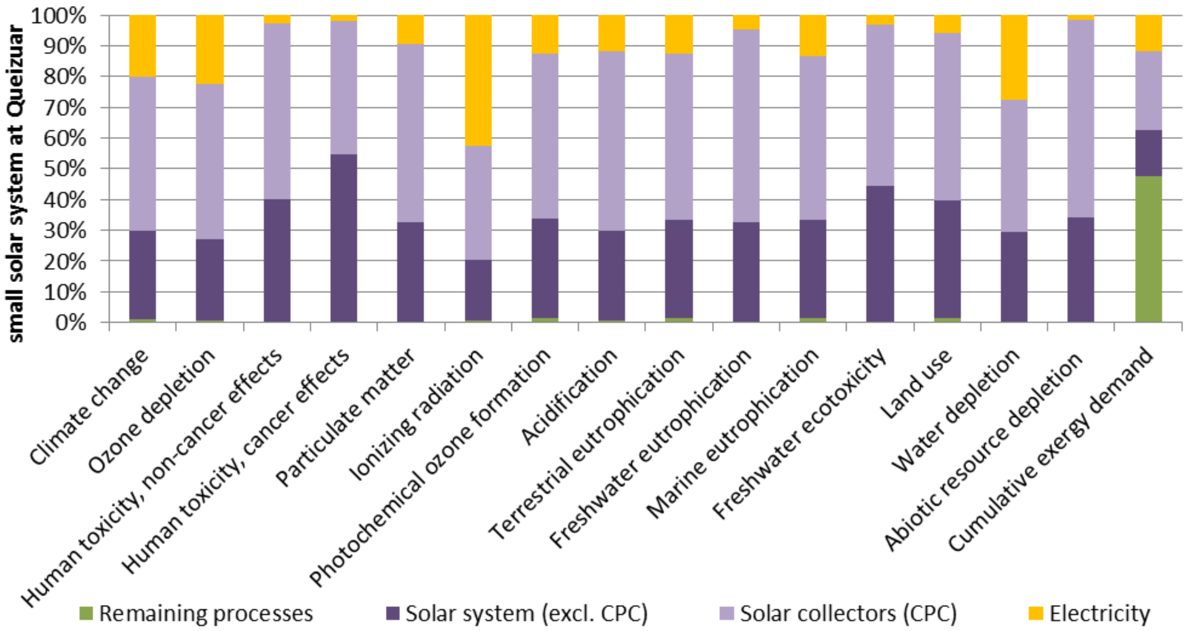

Figure 16 Main contributors to the environmental impacts of the heat at small solar system at Queizuar. The remaining processes include the transport of a van for maintenance and the solar energy input.

An exception from the above mentioned pattern is the impact category cumulative exergy demand: There, the losses of solar energy in the solar system between the collectors and the final use contribute most to the total exergy demand (see “Remaining processes” in Figure 17). The electricity directly used for the circulation of the pump contributes about 10% to the total exergy demand. The method used to assess the cumulative exergy demand of solar exergy has been adapted. For details, please refer to Chapter 3.2.7.6.

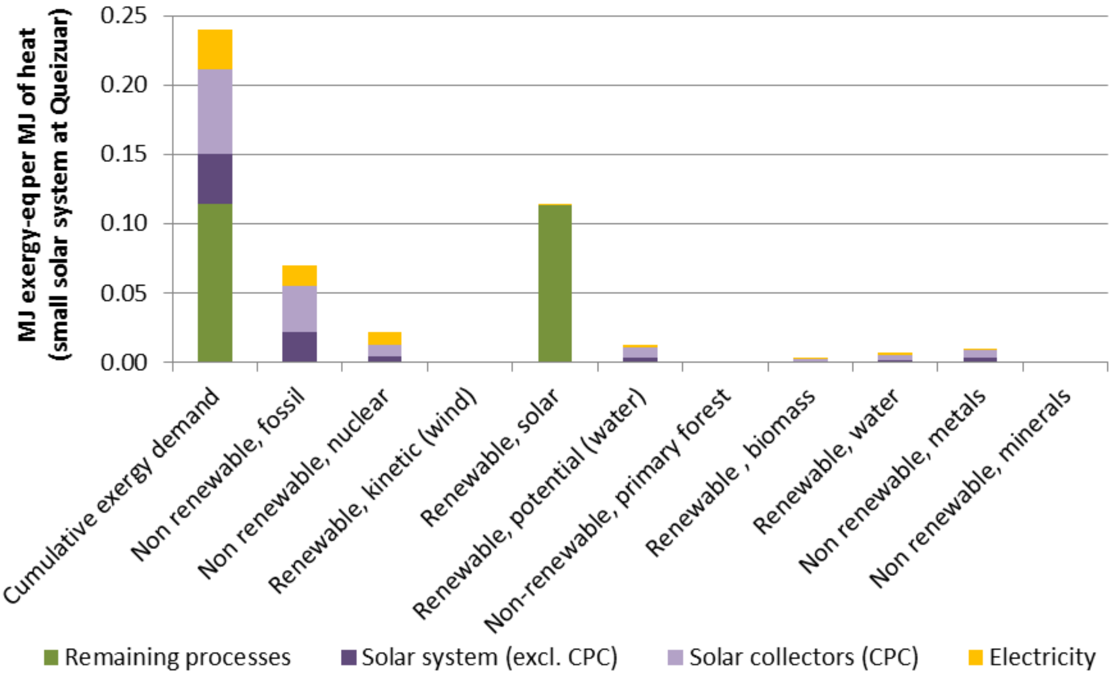

Figure 17 Main contributors to the cumulative exergy demand of the heat at solar collector at Queizuar. The cumulative exergy demand (left) and its split into sub-categories is shown. The remaining processes include the transport of a van for maintenance and the solar energy input.

Main inputs contributing to the total environmental impact

The input of aluminum is responsible for the main impact in most impact categories (Climate change, ozone depletion (same amount as electricity), human toxicity, cancer effect, particulate matter, photochemical ozone formation, terrestrial and marine eutrophication, land use and water resource depletion). Aluminum is both used for the collector (collector tray and reflector) and for the mounting. In acidification, similar impact stem from copper and aluminum input. In most other categories, copper has the main impact (human toxicity, non-cancer effects, freshwater ecotoxicity and eutrophication and abiotic resource depletion). For ionizing radiation, the direct use of electricity for the solar system and the use of aluminum have similar impacts.

The impact categories that show extremely higher results than the reference technology (natural gas boiler) are human toxicity (cancer and non-cancer effects), freshwater eutrophication, freshwater ecotoxicity and abiotic resource depletion.

The processes with the highest impact on human toxicity, cancer effects are disposal processes connected with the production of metals. The main share stems from aluminum (redmud disposal from the bauxite digestion), the rest from steel (disposal of slag) and copper (disposal, sulfidic tailings). The emissions with the highest share in this category are chromium VI emissions to water. For human toxicity, non-cancer effects, the disposal of sulfidic tailings in context with copper has the highest impact. Emissions from zinc and lead to air are the emissions with the highest impact in this category.

In water depletion, the cooling water used for electricity production is the main impact. The electricity is used directly in the system or used for the production of aluminum for the solar system.

Freshwater eutrophication stems from the disposal of sulfidic tailings in copper mining. The emissions with the main impact are phosphor emissions to water. The impact in this category is therefore directly dependent on the amount of copper used for the system.

Also for freshwater ecotoxicity, the metals are the crucial input: copper production (copper emissions to air during production) with highest share (over 70%) and aluminum (again red-mud disposal).

The amount of metal needed per MJ of heat delivered is higher for solar collectors compared to the natural gas boiler. This explains why the impacts are higher in many impact categories.

For the resource depletion, copper used in the solar system adds up to 70% of the total impact in this category.

Analysis of CPC solar collectors

If the mounting system and the operation of the solar system are taken out of the analysis and only the solar collectors are analyzed, the input of metals (copper, aluminum) is the main input in most categories. The electricity use for production does only contribute very little to the total environmental impact.

The environmental impacts of solar collectors are thus dominated by the use of different metals for their production. The longer the collectors are in use and the higher the efficiency of the collector, the less metal is needed per delivered heat. Transport of the materials to the manufacturing place only has a minor influence on the total results. The share of processing (i.e. coating, sheet rolling) on total impact is 5% to 20% (abiotic resource depletion). The focus on efficient solar collectors with a long use time and less metal use can help to reduce the impacts.

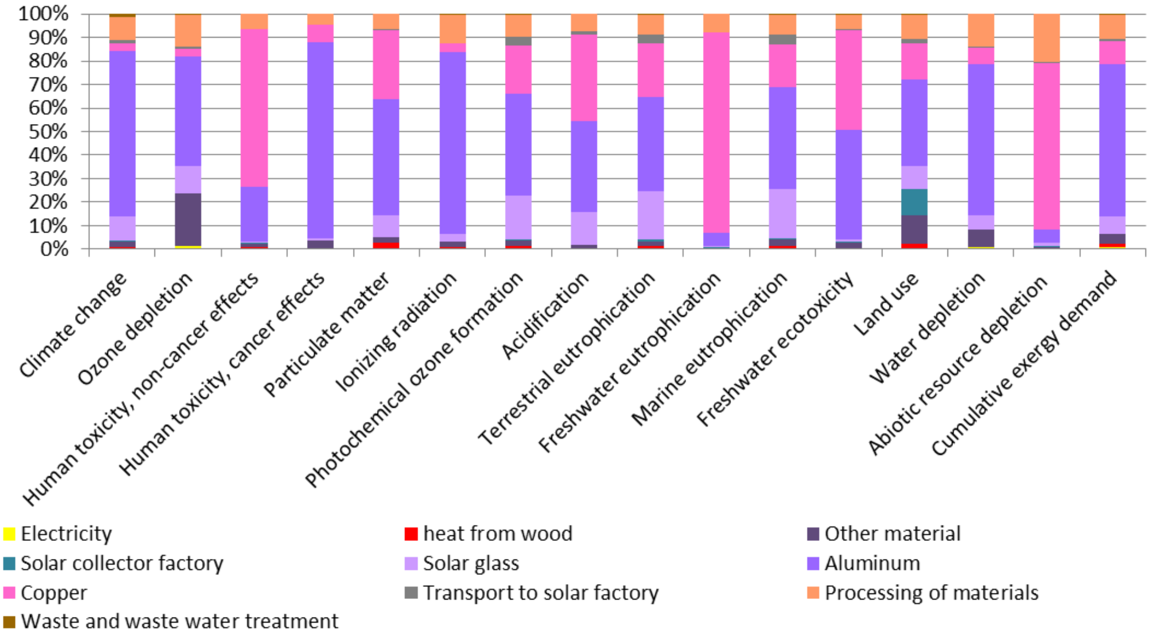

Figure 18 Main contributors to the environmental impacts of the production (incl. materials) of the solar CPC collectors, split into different inputs and outputs of the production process. Solder, chromium steel and packaging are summarized in the group “other material”.

Limits

The small solar system is installed in Spain. The environmental impact of the solar system would be higher if the system would be installed in Oberhausen, where the solar irradiation is lower.

Furthermore, the solar system cannot be used without an additional heating system because it cannot provide all heating demand and does not provide heat at night and less in winter. The analysis of the solar-pellet-system shows that the additional use of pellets to provide the missing heat leads to an increase of the environmental impacts in many categories (see Table 13 and Table 14 for the comparison of heat supply options and Chapter 4.3.8 for details on the pellet boiler). Therefore, another additional heating system should be chosen.

4.3.6. Analysis of heat from large solar collector system

General

The environmental performance of solar collectors heavily depends on the layout of the installation (e.g. alignment, distance between the collectors and the place of heat use, insulation of pipes), the location (irradiation on the collectors, dependent on latitude, climate and local shading effects) and the output temperature of the solar collector system. It is therefore not possible to describe a general result for solar collectors. A lower output temperature increases the yield per collector. The solar system at Queizuar is installed with high output temperature (60° Celsius), whereas the large solar systems are modelled with a low temperature output (37° Celsius). The small solar collector installation on a roof is to a large extent modelled with measured data that is available from the installation at Queizuar in Spain. The models for the large solar collector systems (on open ground and on flat roof) are based on other LCA models and are assuming an installation in Oberhausen, Germany. Thus, the direct comparison of the results from the three solar collector systems is only possible in a limited way.

Main difference of the large solar systems to the small solar system

The heat comparison in Chapter 4.3.1 shows that the impacts of the two large solar systems are lower than the impacts of the small solar system in all impact categories except for land use. There, the large solar system on open ground has extremely higher results than both natural gas and the other solar systems considered. The former use of the land is unknown and the land is transformed to an industrial area. This transformation is the input with the highest contribution to the total impact in the category land use for the large solar collector system on open ground. Another reason is the calculated yield per m^2 which is 25% higher in the modelling for the SUNeco collectors operated with a low temperature (37° Celsius) in Oberhausen compared to the measured yield at Queizuar (60° Celsius).

The share of electricity of total impact is much higher for the large solar collector systems compared to the small solar system. The large solar system models in Oberhausen in Germany use more electricity (factor higher than 1.5) per MJ of delivered heat compared to the small solar system at Queizuar in Spain. Additionally, the solar system plus solar collectors of the large systems has lower impacts compared to the small solar system at Queizuar. These two differences lead to a higher share of electricity for the large solar collector systems.

Main difference between the two large solar systems

The only modelling difference of two large solar collector systems is the installation of the collectors, which is on open ground (with aluminum and concrete) or on a flat roof (with aluminum). Therefore it is not surprising that the split of the impact for heat at the different solar collector systems is very similar except for land use: The impact in this category is more than 100 times higher for the open ground installation compared to the installation on a flat roof. Therefore, the share of the solar system and its land use accounts for almost all impact for the system on open ground, whereas for the main share for the installation on flat roof is the solar collector: the production of plant fibers for cardboard production used for packaging has the highest impact, the solar collector factory itself only amounts to 10% of total impact.

Similarities of the two large solar systems

The solar collectors have the main impact in most categories. For the impact category climate change, ozone depletion, ionizing radiation, water depletion, the electricity for operating the solar system has the highest share. Only for land use of the large solar system on open ground, the solar system has the highest share.

The results of the cumulative exergy demand of the two large solar systems are in the same range (see Figure 17). Also the shares do not deviate between the systems: The solar exergy accounts for almost half of the total demand, followed by electricity, the solar collectors and the solar system (excl. the collectors).

Results of the two large solar collector systems

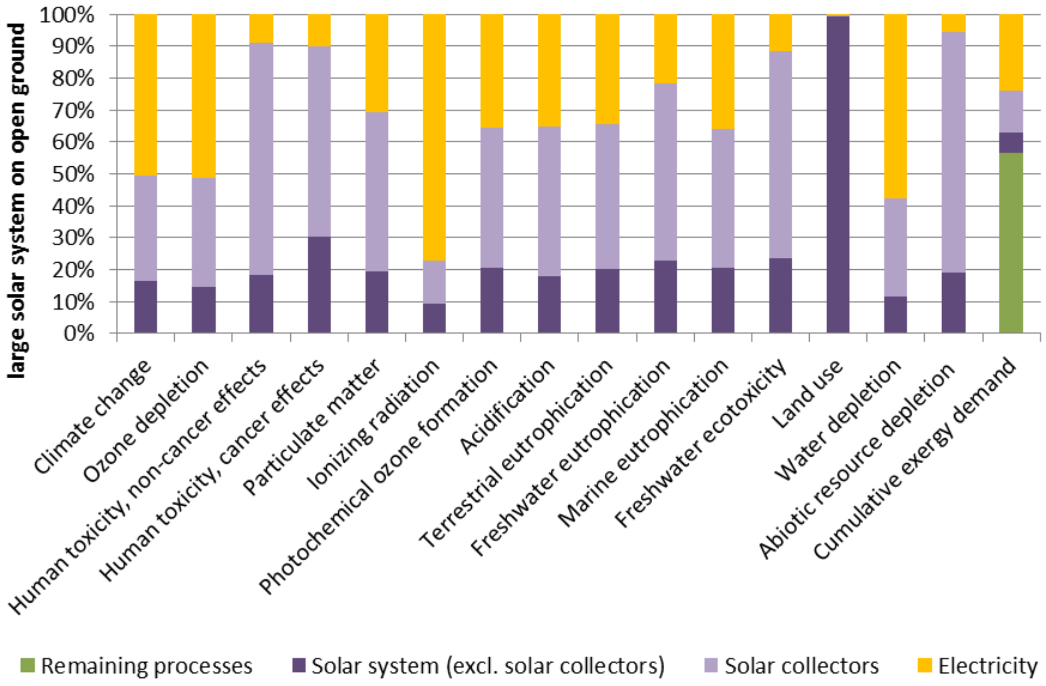

Figure 19 Main contributors to the environmental impacts of the heat at large solar collector system on open ground in Oberhausen. The remaining processes include the transport of a van for maintenance and the solar energy input.

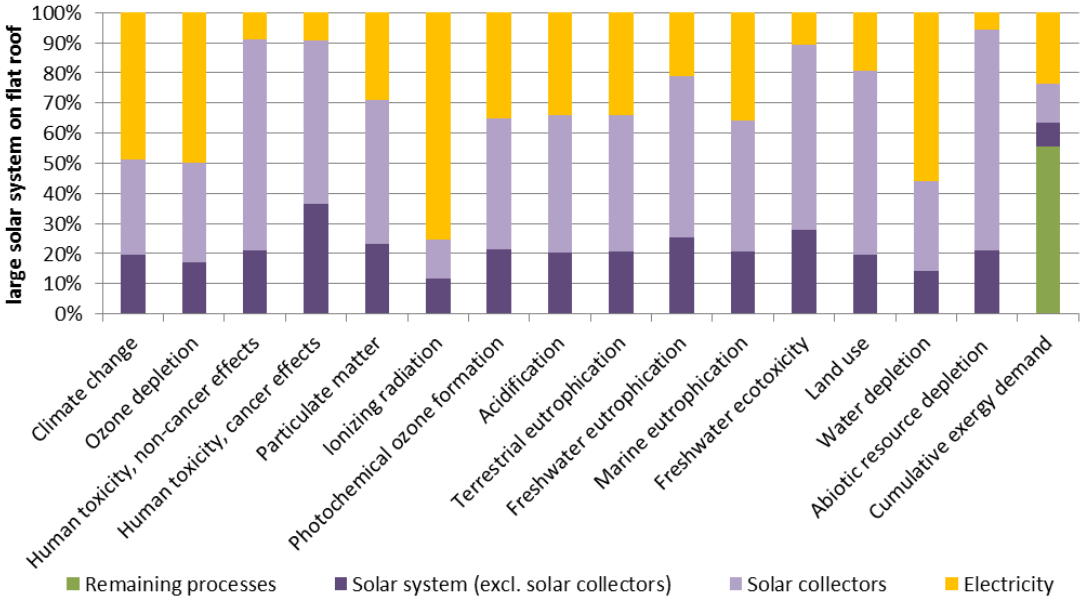

Figure 20 Main contributors to the environmental impacts of the heat at large solar collector system on flat roof in Oberhausen. The remaining processes include the transport of a van for maintenance and the solar energy input.

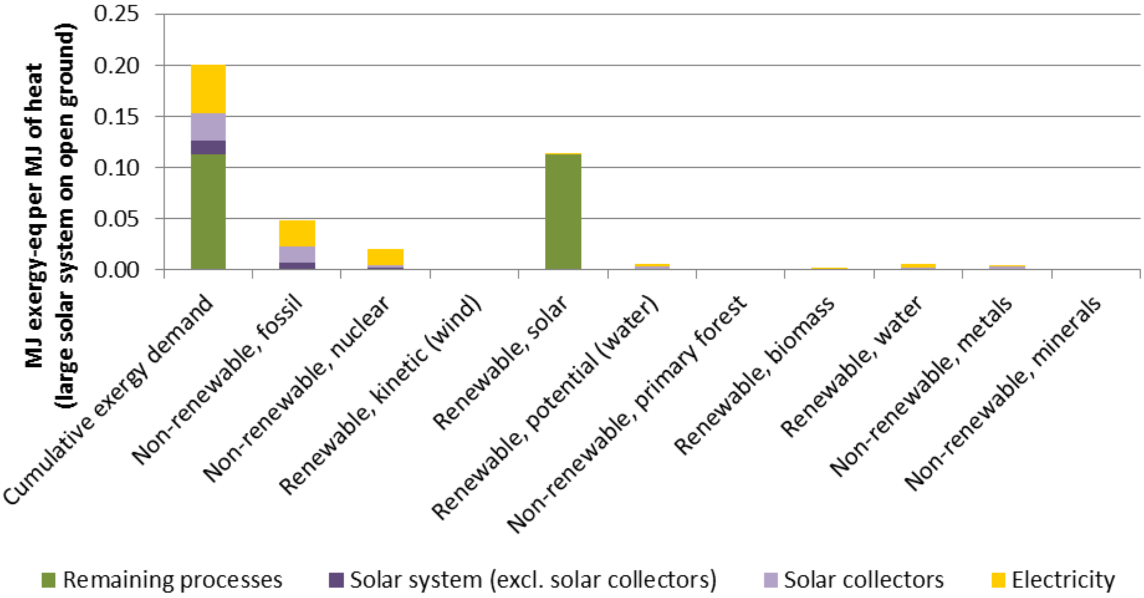

Figure 21 Cumulative exergy demand of the heat at large solar collector system on open ground in Oberhausen in MJ-eq per MJ heat delivered. The cumulative exergy demand (left) and its split into sub-categories is shown. The remaining processes include the transport of a van for maintenance and the solar energy input.

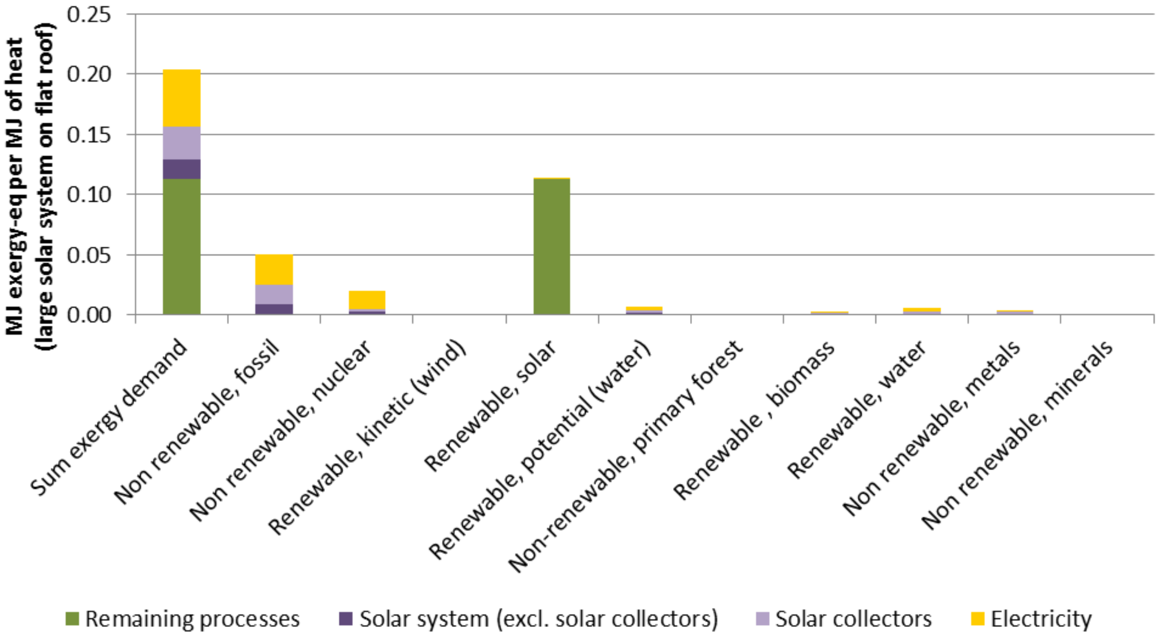

Figure 22 Cumulative exergy demand of the heat at large solar collector system on flat roof in Oberhausen in MJ-eq per MJ heat delivered. The cumulative exergy demand (left) and its split into sub-categories is shown. The remaining processes include the transport of a van for maintenance and the solar energy input.

Analysis of SUNeco solar collectors

At the small solar system at Queizuar, CPC collectors are used. For the large solar collector systems, SUNeco solar collectors are used in the modelling. The SUNeco collectors have a lower impact in all categories per unit.

The main difference to the CPC collectors are the share of processing that is much higher for the SUNeco collectors. There, two processes have the main impact, the coating of the aluminum absorber and the coating of the steel collector. Since the SUNeco collectors consist of less aluminum and copper and less steel, these shares are smaller as well.

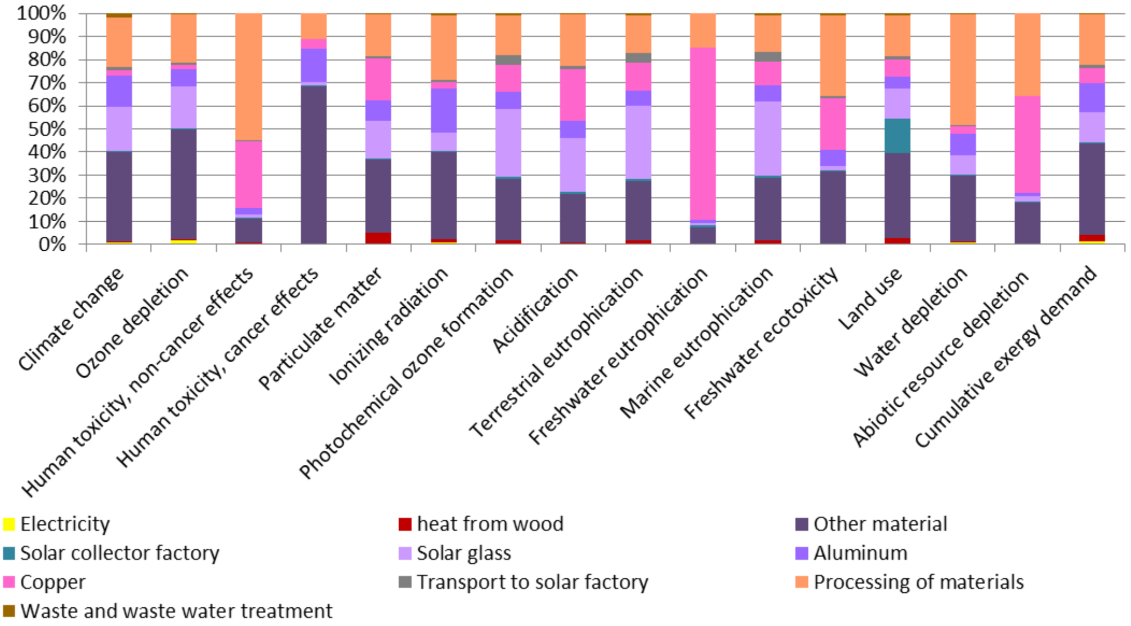

Figure 23 Main contributors to the environmental impacts of the production (incl. materials) of the solar SUNeco collectors, split into different inputs and outputs of the production process. Solder, chromium steel and packaging are summarized in the group “other material”.

4.3.7. Analysis of heat from gas-engine driven heat pump

The burning of natural gas to drive the heat pump contributes the most to the total impact in most categories (see Figure 24). In two impact categories, the auxiliary electricity has the highest potential impacts: For ionizing radiation, the nuclear share of the European electricity mix is the main input. Therefore, the auxiliary electricity directly used in the operation of the gas engine contributes most in this impact category. Also for water depletion, the auxiliary electricity has the main impact. It stems from the cooling water used in the context of electricity (cooling tower of lignite, hard coal and nuclear power plant).

For the abiotic resource depletion, the use of the heat pump is in the same range as the natural gas boiler (see Figure 10). The production of the heat pump contributes most to this type of impacts. The main input stems from electronics (82%, from depletion of tantalum, silver and gold) whereas the cable (8%) and the steel input (6%) contribute less. About 10% stems from the electricity used in the life cycle of the heat pump production (mainly the uranium depletion for nuclear electricity). A quarter of the total impact for the abiotic resource depletion stems from the natural gas burned to drive the heat pump.

For human toxicity, non-cancer effects, the disposals in connection with electronics and cable contribute one third to the total impact. The disposal of spoil from lignite production as part of the European electricity mix contributes about one fifth.

For human toxicity, cancer effects, the iron production respectively finally the chromium VI emissions from that process cause the main impact. The iron is mainly used for natural gas provision and cannot be influenced by the heat pump producers nor by users.

The CO_2-emissions from burning natural gas in the gas engine cause the main impact on climate change. These emissions could only be influenced indirectly by an increase of the cooling efficiency that is not trivial. Some climate change effects stem from methane emissions that mainly occur due to losses during the transport of natural gas of in long-distance pipelines (methane is the main component of natural gas).

For particulate matter, the emissions of particles from the combustion process have the main impact. For photochemical ozone formation, acidification, terrestrial and marine eutrophication, the emission of nitrogen oxides during the combustion process at the heat pump causes the main impact. These emissions can be influenced by the developers by reducing the amount of nitrogen oxides emitted in the burning process.

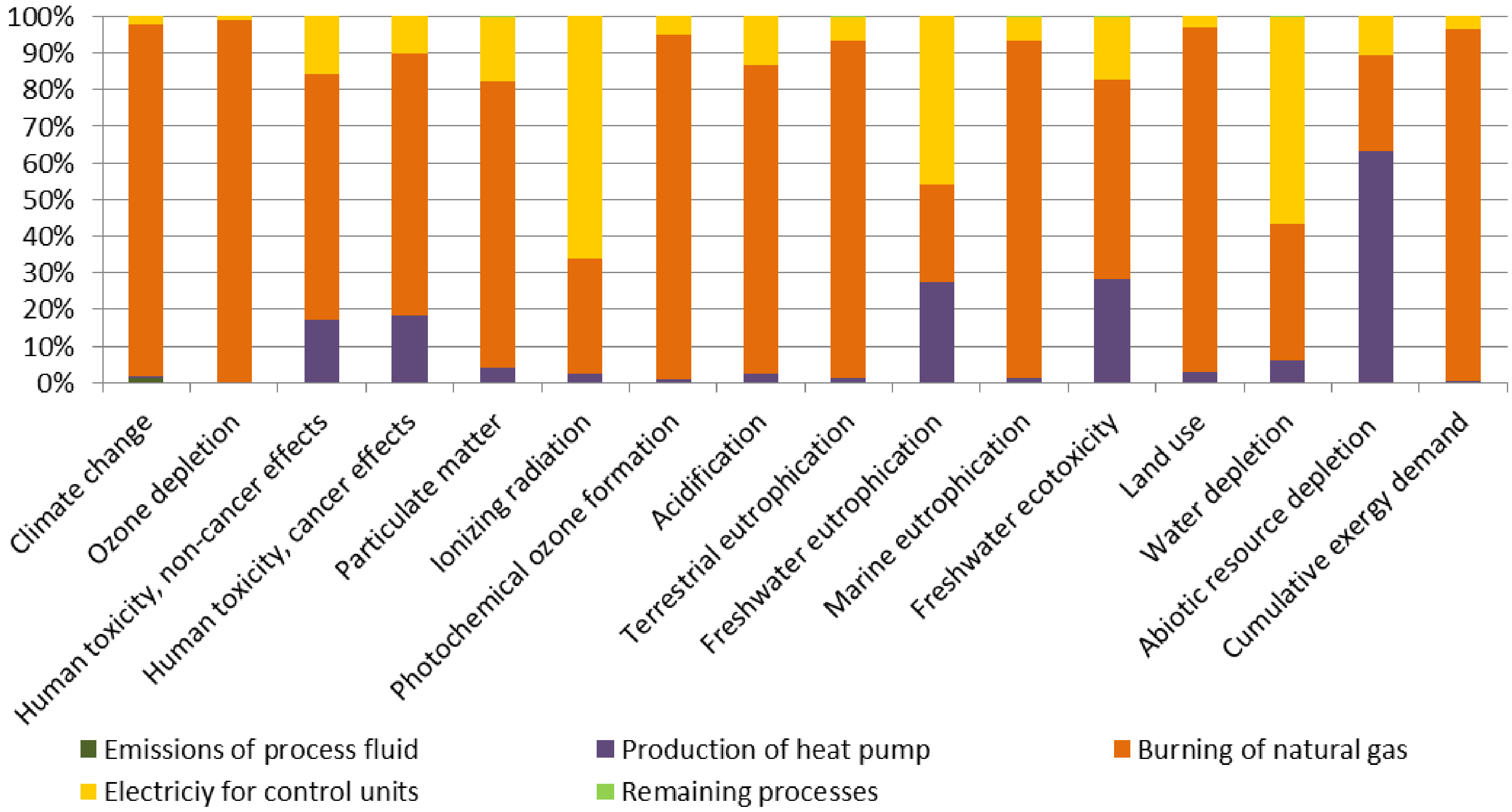

Figure 24 Main contributors to the ILCD impact categories of the heat at the gas-engine driven heat pump. The remaining processes consist of the transport of the heat pump from production to the destination and the input of new process liquid due to losses.

The process burning of natural gas is analyzed further in Figure 25. It includes the natural gas input, the emissions and other inputs needed for operation like lubricant oil. The natural gas provision can only be influenced indirectly by increasing the efficiency of the heat supply. If only the impact from burning of natural gas are assessed (without input of heat pump and electricity), the emissions from the burning process have a share of more than one quarter in the impact categories climate change, particulate matter, photochemical ozone formation, acidification, terrestrial and marine eutrophication. There, the engine plays an important role on the effects.

Limits

The heat pump with this configuration needs waste heat at 60°C. If no waste heat at this temperature is available, the efficiency of the process is lower. The lower the temperature difference between the heat source and the heat required, the more efficient the heat pump performs.

Summary

The efficiency of the heat pump (natural gas needed per MJ of heat provided) is an important factor influencing all results. The electronics used for the heat pump are the crucial factor for the impact category abiotic resource depletion. The emissions from the gas engine, especially the nitrogen oxide emissions, have a crucial impact in many categories.

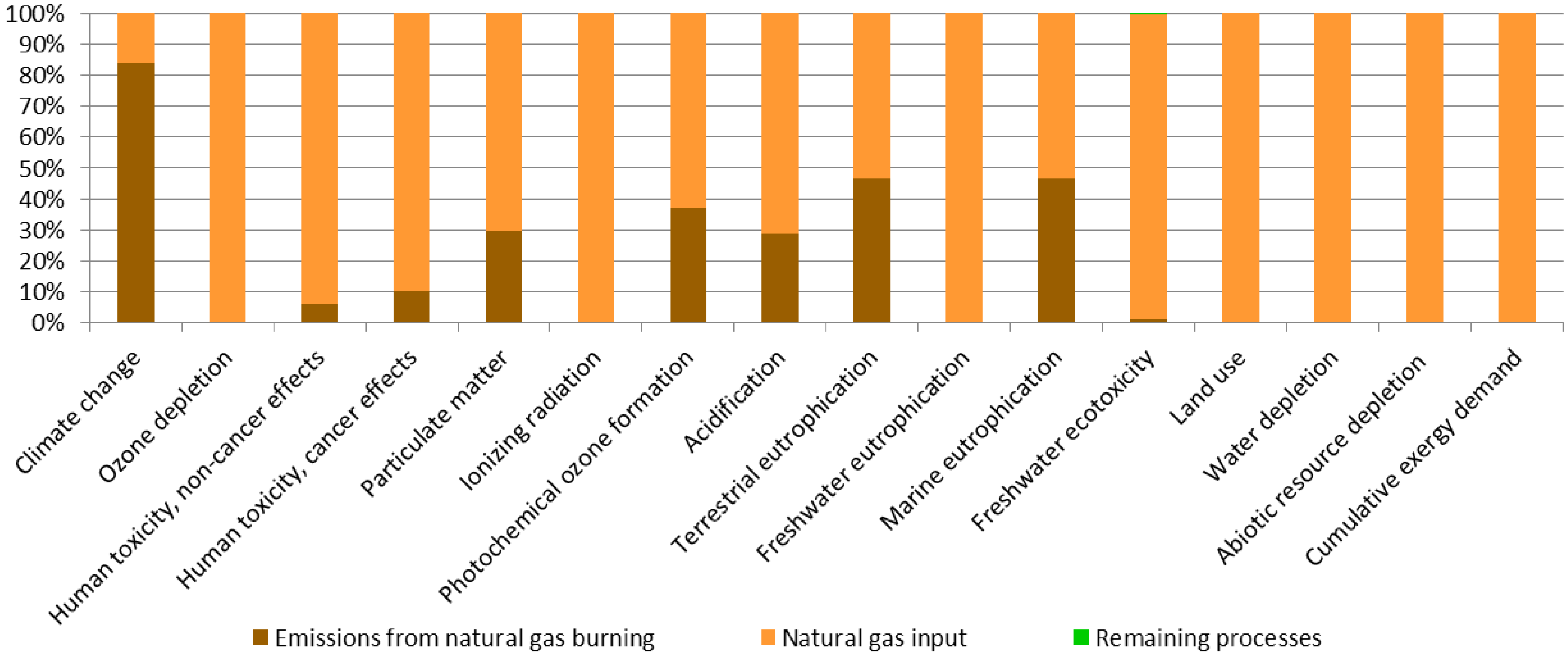

Figure 25 Main contributors to the ILCD impact categories of the burning of natural gas in the gas-engine driven heat pump, consisting of the emissions from burning natural gas, the gas provision, and remaining processes (input and disposal of lubricating oil).

4.3.8. Analysis of heat from pellet boiler

Pellet boiler without particle separator

For the analysis of heat at pellet boiler, the impact is split into different input groups as depicted in Figure 26. The disposal of wood ash is included in “burning of pellets”. It contributes less than three percent of the total impact of each category.

The burning of the pellets is the main contributor in human toxicity, cancer effect, particulate matter, photochemical ozone formation, acidification, terrestrial and marine eutrophication. The burden in the category human toxicity, non-cancer effects stems from the emissions of metals (mainly zinc into the air) during the burning of the pellets. These are rather uncertain estimations which depend on the fuel quality and might be quite variable. The burden in the category particulate matter originates from the direct emission of particles from the burning of the pellets in the boiler. The value is based on real measurements and thus points to an important improvement option.

The production of the wood pellets contribute most to climate change, ozone depletion, human toxicity, cancer effect, ionizing radiation, freshwater eutrophication, freshwater ecotoxicity, land use, water depletion, abiotic resource depletion and cumulative exergy demand. The wood pellets are assumed to be produced from wood residue, as a by-product of wood processing. The environmental burden allocated to the wood input is therefore smaller than if pellets were directly produced from forest wood. For the cumulative exergy demand, more than 70% of the total stem from the sub-category renewable, biomass and originate from the wood pellets. For the impact category climate change, the electricity use has the main influence on the result. It is used for the production of the pellets (40%) and the direct use at the dairy for the operation of the pellets boiler (10%). The ionizing radiation stems from nuclear electricity production that is mainly from the French part of the European electricity mix. Also for the pressing of pellets, the European electricity mix is used.

The production of the pellet boiler only has a crucial impact for the category human toxicity, cancer effect, where the steel production mainly contributes to the impact.

Limits

The pellet boiler analyzed in this study only provides 70kW. This pellet boiler is therefore only fitting to dairies that have a heat demand that is below this number.

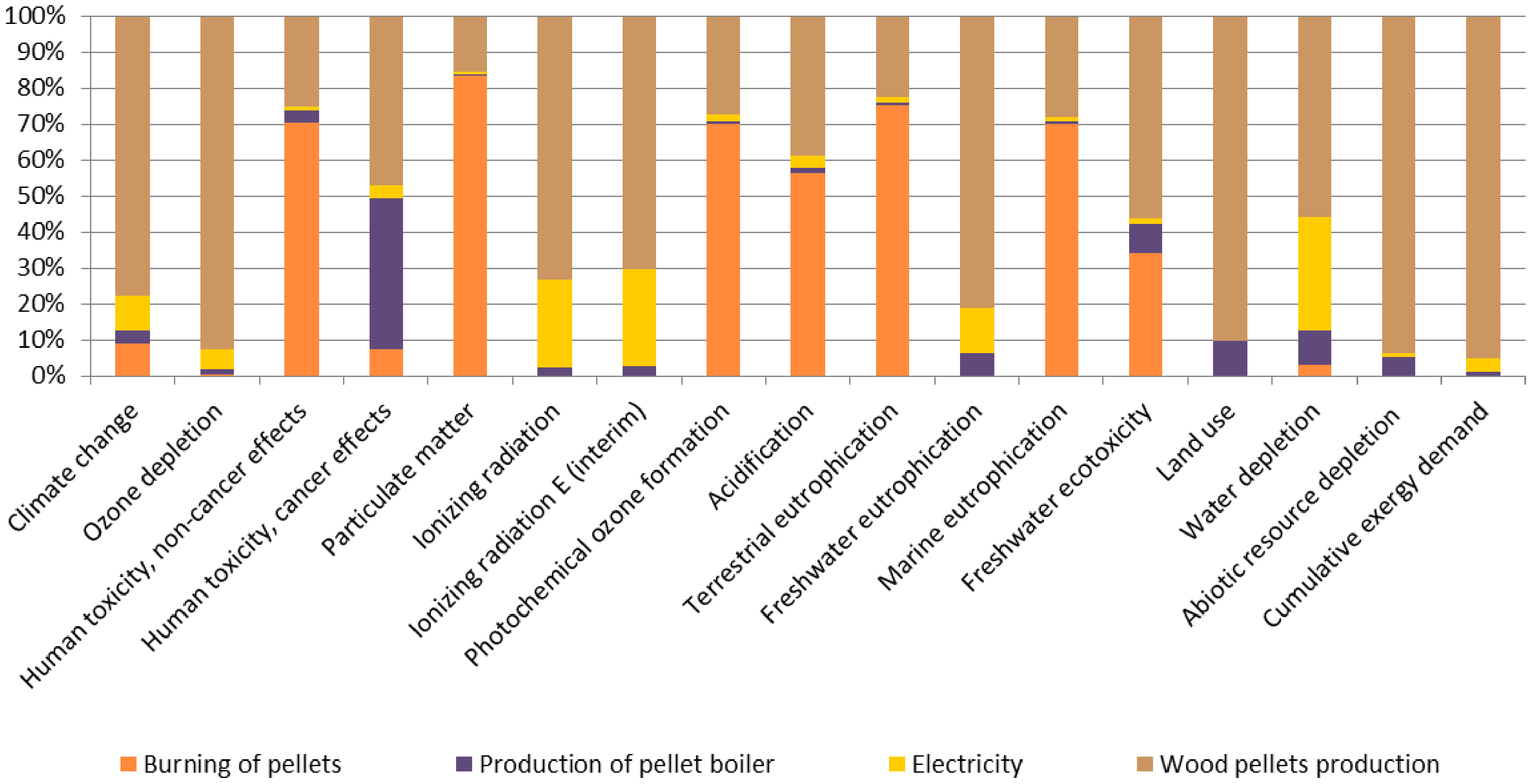

Figure 26 Main contributors to the ILCD impact categories of the heat at pellet boiler without particle separator split into different groups. The disposal of wood ash contributes little and is included in the group “Burning of pellets”.

Pellet boiler with particle separator

The pellet boiler with particle separator is modelled with an additional input of metal for the separator, an additional electricity demand and a reduction of particle emissions by 70%. The results in most categories only increase slightly with the integration of the particle separator (below 3%) and therefore do not change the shares on total impact of the considered processes. In the impact category "particulate matter", a reduction of 69% can be achieved. This reduction shifts the share of the burning process of total impact from 85% to 70%.

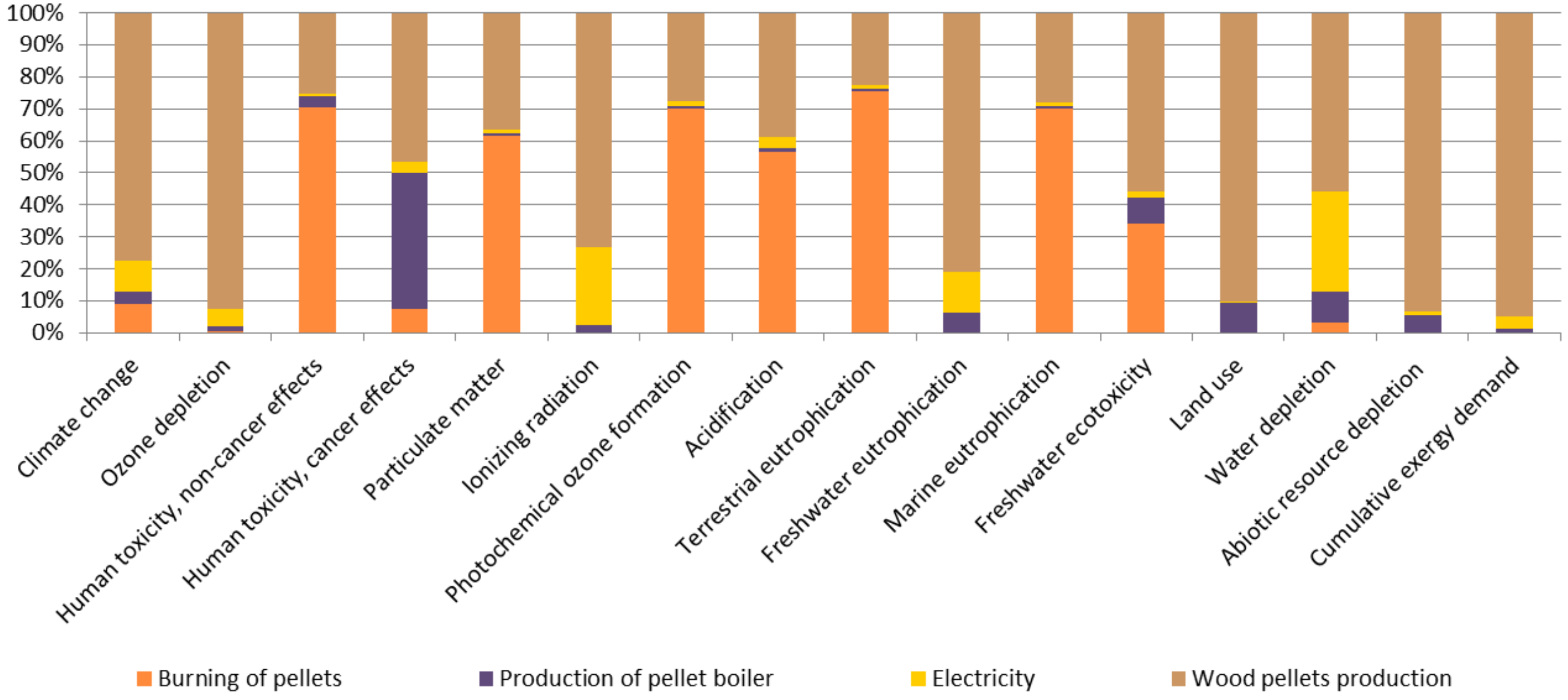

Figure 27 Main contributors to the ILCD impact categories of the heat at pellet boiler with particle separator, split into different groups. The disposal of wood ash contributes little and is included in the group "Burning of pellets".

4.4. Electricity supply

If combined heat and power (CHP) systems are used to provide heat, electricity is also produced with the CHP and does not originate from the grid. Therefore it is important compare the environmental burden of the electricity from CHP with the European mix (standard) to account for all changes that happen if the system is changed. The electricity from different CHP systems (gas motor, gas turbine and wood) is compared to the electricity grid. A description of the datasets used is given in the table below.

Table 17 Overview and description of the electricity processes which are compared and analyzed

Short name	Exact name of process (LINK)	Source	Power (kW)	Comment
Grid	electricity, medium voltage, at grid/RER	Itten et al. 2012	-	Reference: European grid mix.
Cogen. (motor), natural gas	Electricity, at cogen 1MWe lean burn, allocation exergy/RER	Heck 2007	1'000 (electric)	Generic data: 1MW electric with 38%electric, 44% heat. (Heck 2007, Table. 3.1)
Cogen. (turbine), natural gas	electricity, natural gas, at turbine, 10MW, allocation exergy/GLO	This study, based on Faist Emmenegger et al. 2007	10'000 (electric)	Own assumption 11% electric, 67% heat with 0.11 MJ-eq exergy per MJ heat
Cogen., wood	electricity, at cogen 6400kWth, wood, emission control, allocation exergy/RER	Bauer 2007	6400 (thermal)	Large CHP for wood to be installed at the dairy. 8.3% electric efficiency, 80% heat with 0.335 MJ-eq exergy per MJ heat

The relative change of the environmental impact in different categories (see Figure 28) shows that cogeneration (motor) with natural gas is better in several impact categories. Exception is the impact category ozone depletion. Since the result of this category is considered less reliable than the result of other categories (see Chapter 5.1.2), the negative result is not crucial for the final evaluation. If one of these two CHP systems is used, the change of the electricity will not change the overall result in a negative way and the improvements described for heat can be maintained or even enlarged. The highest impact on ozone depletion stems from the transport of natural gas in pipelines for all except for the cogeneration with wood, where the production of crude oil is the main input.

For the cogeneration (turbine) with natural gas, the result is less clear, since the gas turbine is worse in about half the categories. The cogeneration with wood is better in two third of the impact categories and worse in one third. Electricity from cogeneration with wood is therefore rather an improvement compared to electricity from European grid.

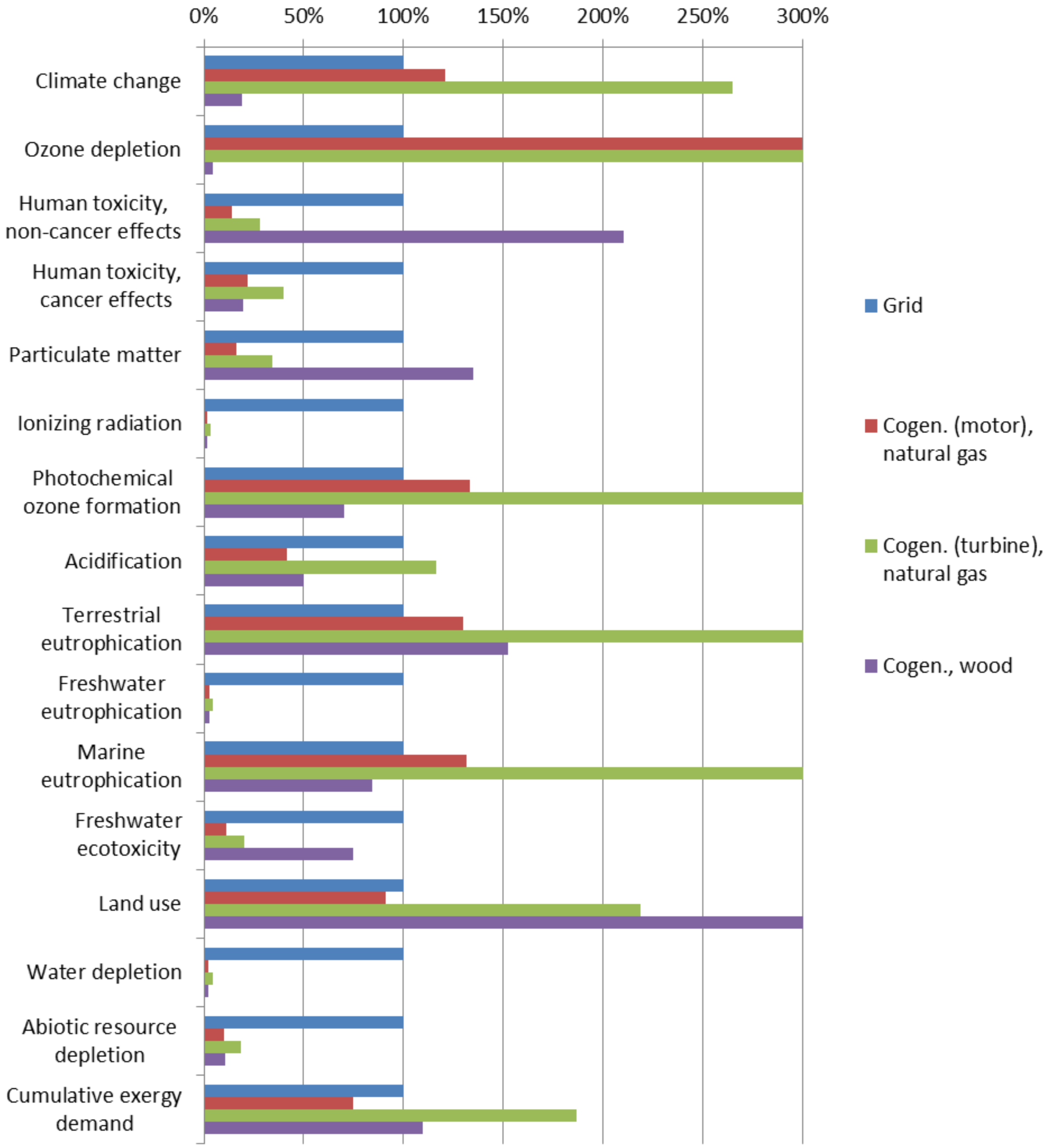

Figure 28 ILDC impact categories and cumulative exergy demand: Comparison of electricity from different types of cogeneration, given as percentage of the reference scenario (electricity from grid, always 100%). Formula used: Value of option / Reference value. If the value is more than three times the reference, the value is not shown. Please refer to the table below.

The results depicted in the figure above are as well presented in the table below, showing the environmental impact in comparison to the reference which is the electricity from grid.

Table 18 ILDC impact categories: Comparison of electricity supply options, given in percentage of the reference scenario (electricity from European Grid, always 100%, not shown). Formula used: Value of option / Reference value. Increases are in red and lightly shaded, reductions are in green and without shade. The darker the color, the further away is the result from the reference value.

	Cogen. (motor), natural gas	Cogen. (turbine), natural gas	Cogen., wood
Climate change	121%	**265%**	**19%**
Ozone depletion	**300%**	**636%**	**4%**
Human toxicity, non-cancer effects	**14%**	28%	**211%**
Human toxicity, cancer effects	**22%**	40%	**20%**
Particulate matter	**16%**	35%	135%
Ionizing radiation	**1%**	**3%**	**2%**
Photochemical ozone formation	134%	**349%**	70%
Acidification	42%	116%	50%
Terrestrial eutrophication	130%	**374%**	153%
Freshwater eutrophication	**2%**	**4%**	**3%**
Marine eutrophication	132%	**379%**	84%
Freshwater ecotoxicity	**11%**	**20%**	75%
Land use	91%	**219%**	**309%**
Water depletion	**2%**	**4%**	**2%**
Abiotic resource depletion	**10%**	**19%**	**11%**
Cumulative exergy demand	75%	187%	110%

Table 19 presents the calculated results for the ILCD impact categories and the cumulative exergy demand in absolute values per kWh of electricity delivered.

Table 19 ILDC impact categories: Comparison of electricity supply options given in absolute values per kWh of electricity

		Grid	Cogen. (motor), natural gas	Cogen. (turbine), natural gas	Cogen., wood
Climate change	kg CO2 eq	4.87E-01	5.89E-01	1.29E+00	9.35E-02
Ozone depletion	kg CFC-11 eq	2.25E-08	6.73E-08	1.43E-07	1.00E-09
Human toxicity, non-cancer effects	CTUh	2.70E-08	3.74E-09	7.63E-09	5.68E-08
Human toxicity, cancer effects	CTUh	3.28E-09	7.08E-10	1.30E-09	6.51E-10
Particulate matter	kg PM2.5 eq	1.53E-04	2.52E-05	5.29E-05	2.07E-04
Ionizing radiation	kBq U235 eq	1.22E-01	1.76E-03	3.80E-03	2.19E-03
Photochemical ozone formation	kg NMVOC eq	9.31E-04	1.24E-03	3.25E-03	6.55E-04
Acidification	molc H+ eq	2.15E-03	8.99E-04	2.51E-03	1.08E-03
Terrestrial eutrophication	molc N eq	3.27E-03	4.25E-03	1.22E-02	4.99E-03
Freshwater eutrophication	kg P eq	4.41E-05	1.09E-06	1.89E-06	1.23E-06
Marine eutrophication	kg N eq	2.94E-04	3.87E-04	1.12E-03	2.48E-04
Freshwater ecotoxicity	CTUe	9.81E-02	1.12E-02	1.99E-02	7.32E-02
Land use	kg C deficit	1.57E-01	1.43E-01	3.43E-01	4.85E-01
Water depletion	m3 water eq	2.70E-03	5.43E-05	1.13E-04	6.21E-05
Abiotic resource depletion	kg Sb eq	1.83E-06	1.85E-07	3.41E-07	1.95E-07
Cumulative exergy demand	MJ-eq	1.16E+01	8.64E+00	2.16E+01	1.27E+01

4.5. Cooling

In this chapter different options for the cooling in the dairy are compared and analyzed. The following questions are answered in this chapter:

- Which influence on the environmental impacts can be expected by implementing state of the art and new technologies developed in the SUSMILK project in existing European dairies instead of the cooling by electric chiller? (Chapter 4.5.1)
- Which factors are relevant for the cause of environmental impacts? (Chapter 4.5.1, 4.5.2, 4.5.3 and 4.5.4)
- Where shall technology partners put their focus on in order to improve the technology options? (Chapter 4.5.4)

4.5.1. Comparison of cooling options

The cooling demand of the generic dairy is about 2’200 kW (assuming 20h operation per day). Alternative technologies have been chosen with a size that is closest to the needed cooling demand.

The following options are compared in this section:

- Conventional technology used in the generic dairy
  - Ice water at electric chiller (0.5°C)
  - Cold water at electric chiller (12°C)
- Improvement options
  - two datasets from this study: cold water from absorption chiller (7°C), with heat from cogeneration and waste heat
  - one dataset with generic data: cold water from absorption chiller (6°C), with heat from cogeneration
  - one dataset from this study: groundwater cooling (12°C)

All options are described in more detail in the table below.

Table 20 Overview and description of the cooling processes which are compared and analyzed

Short name	Exact name of process	Source	Power (kW)	Comment
Ice water, 0.5°C, at electric chiller	ice water, 0.5°C, at electric compressor/RER	This study	460	Reference. Average power calculated with daily cooling provided with ice water.
Cold water, 6°C, at absorption chiller 100 kW (heat from cogen)	Cooling energy, natural gas, at cogen unit with absorption chiller 100kW/RER	Primas 2007	100	Single stage absorption chiller with 100 kW cooling capacity, connected to a 250 kW hybrid air cooler. Heat input from a 160 kWel cogeneration unit with natural gas. Electricity adapted to dairy mix. Allocation between electricity and heat according to exergy.
Cold water, 7°C, at absorption chiller 50 kW (waste heat)	cold water, waste heat, 7°C, at absorption chiller, 50kW/RER	This study	50	
Cold water, 7°C, at absorption chiller 50 kW (heat from cogen)	cold water, cogen heat, 7°C, at absorption chiller, 50kW/RER	This study	50	Heat from a 1 MWe cogeneration plant, driven by natural gas. Allocation between electricity and heat according to exergy.
Cold water, 12°C, at electric chiller	cold water, 12°C, at electric compressor/RER	This study	1700	Average power calculated with daily cooling provided with cold water.
Cold water, 12°C, at groundwater pump	cold water, 12°C, at groundwater pump/RER	This study	depending on water flow	Cold water, 12°C, at groundwater pump

As cooling method used in the generic dairy model, an electrical chiller is used. It serves as a reference value for comparison with the improvement options and generic data. The results for the impact categories recommended by the ILCD are depicted first, followed by the results for the cumulative exergy demand.

The equipment needed to produce cooling is not modelled in a detailed way for the generic dairy but only assessed roughly. Therefore, the material need is underestimated for the ice water and cold water at electrical chiller. The results of the abiotic resource depletion have therefore less explanatory power.

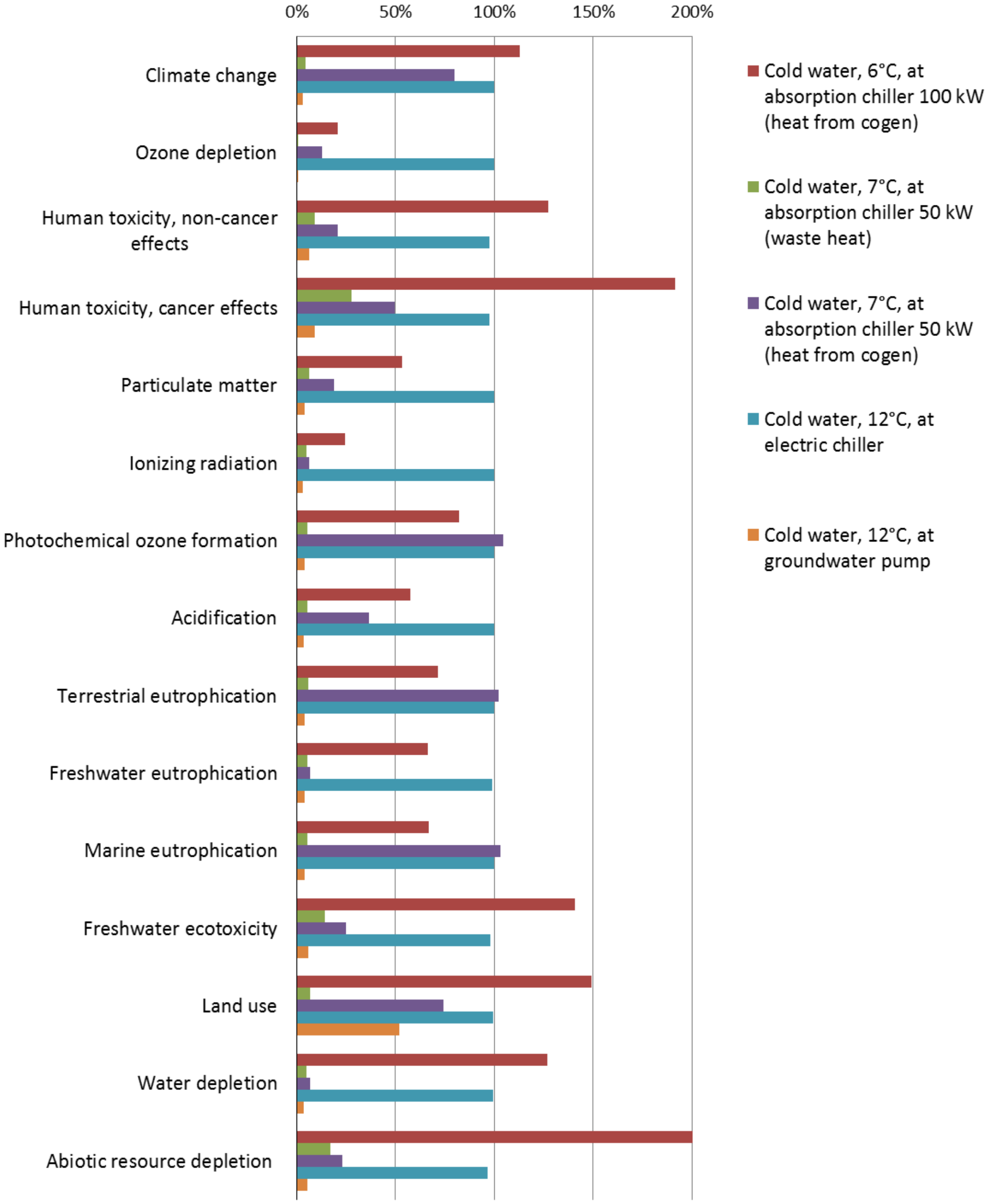

Figure 29 ILDC impact categories: Comparison of cooling, given in percentage of the reference (ice water, 0.5°, at electric chiller, always 100%, not shown). Formula used: Value of option / Reference value. If the option has more than twice the burden of the reference, the value is not shown in the graph (Cold water, 6°C: abiotic resource depletion). Please refer to the table below.

Table 21 ILDC impact categories: Comparison of cooling, given in percentage of the reference (ice water, 0.5°, at electric chiller, always 100%, not shown). “Cold water, 6°C” is modelled in ecoinvent, the other datasets are modelled for this study. Formula used: Value of option / Reference value. Increases are in red and lightly shaded, reductions are in green and without shade. The darker the color, the further away the result is from the reference value.

Impact Category	Cold water, 6°C, at absorption chiller 100 kW (heat from cogen)	Cold water, 7°C, at absorption chiller 50 kW (waste heat)	Cold water, 7°C, at absorption chiller 50 kW (heat from cogen)	Cold water, 12°C, at electric chiller	Cold water, 12°C, at groundwater pump
Climate change	113%	**4%**	80%	100%	**3%**
Ozone depletion	**21%**	**0%**	**13%**	100%	**0%**
Human toxicity, non-cancer effect	127%	**9%**	**21%**	97%	**6%**
Human toxicity, cancer effects	191%	28%	49%	97%	**9%**
Particulate matter	53%	**6%**	**19%**	100%	**4%**
Ionizing radiation	**25%**	**5%**	**6%**	100%	**3%**
Photochemical ozone formation	82%	**5%**	105%	100%	**4%**
Acidification	57%	**5%**	36%	100%	**4%**
Terrestrial eutrophication	72%	**6%**	102%	100%	**4%**
Freshwater eutrophication	66%	**5%**	**7%**	99%	**4%**
Marine eutrophication	67%	**5%**	103%	100%	**4%**
Freshwater ecotoxicity	141%	**14%**	**25%**	98%	**6%**
Land use	149%	**7%**	74%	100%	52%
Water depletion	127%	**5%**	**7%**	99%	**3%**
Abiotic resource depletion	**234%**	**17%**	**23%**	97%	**5%**

There are huge differences in the assessment for the two absorption chillers which use heat from a natural gas co-generation unit. Both use about the same amount of heat (with the same impacts) per MJ of cooling. The larger facility (100kW) is modelled in ecoinvent and has about ten times the weight compared to the facility (50kW) modelled in this project. This leads to much higher impacts due to the material use. The large facility also uses about 5 times more electricity in operation (from European grid) and thus has also higher impacts than the one modelled in this project. Even if technologies are very similar, they thus show very different impacts.

Alternatives to cooling with electricity are better in most categories (see Figure 29 and Table 21). The cooling with the smaller absorption chiller (50kW) and groundwater cooling are better in all categories, whereas the larger absorption chiller (100kW, generic ecoinvent data) that uses heat from a combined heat and power system driven by natural gas, is worse in seven impact categories, namely climate change (only a bit higher), human toxicity (cancer and non-cancer effects), freshwater ecotoxicity, land use, water depletion and abiotic resource depletion. A reduction between 70% and almost 100% is possible in the impact categories if the smaller waste-heat driven absorption chiller is implemented. If a groundwater pump replaces the electrical chiller, a reduction of over 90% in all categories except land us is possible, where the reduction is around 50%.

The amount of copper and steel modelled for the larger absorption chiller (100kW) is bigger compared to the reference (electrical cooling), leading to a higher environmental impact in the impact category human toxicity, non-cancer effect. For the cancer effect, a main difference is the amount of ferrochromium used which is higher for the larger absorption chiller (100kW) with a natural gas cogeneration unit than for the other cooling processes.

The environmental impact for freshwater ecotoxicity of the larger absorption chiller (100kW) also mainly stems from steel and copper inputs.

In the impact category land use, the process “well for exploration onshore” needed to extract natural gas and crude oil (used both for electricity production and directly in the heat production process at the dairy) has the main impact and can therefore be influenced by the total amount of natural gas and oil used for the cooling with cogeneration units or the total amount of electricity used. For the groundwater cooling, the pump station is the process with highest impact.

For abiotic resource depletion, the different amount of ferronickel and copper used account for the higher impact for the larger absorption chiller (100kW) with heat from cogeneration with natural gas.

Since the equipment for the electrical cooling is underestimated, these different amounts of material use could be due to modelling choices and not real differences.

In general and in short, all modelled alternative ways of cooling can be recommended but the larger absorption chiller (100kW) modelled in ecoinvent cannot be generally recommended.

Table 22 ILDC impact categories: Comparison of cooling given in absolute values per MJ cooling energy provided

Impact Category	Unit	Ice water, 0.5°C, at electric chiller	Cold water, 6°C, at absorption chiller 100 kW (heat from cogen)	Cold water, 7°C, at absorption chiller 50 kW (waste heat)	Cold water, 7°C, at absorption chiller 50 kW (heat from cogen)	Cold water, 12°C, at electric chiller	Cold water, 12°C, at groundwater pump
Climate change	kg CO2 eq	5.40E-02	6.10E-02	2.33E-03	4.30E-02	5.40E-02	1.65E-03
Ozone depletion	kg CFC-11 eq	3.65E-08	7.61E-09	1.07E-10	4.75E-09	3.65E-08	6.89E-11
Human toxicity, non-cancer effects	CTUh	2.59E-09	3.30E-09	2.35E-10	5.31E-10	2.52E-09	1.63E-10
Human toxicity, cancer effects	CTUh	3.16E-10	6.04E-10	8.68E-11	1.56E-10	3.07E-10	2.85E-11
Particulate matter	kg PM2.5 eq	1.43E-05	7.63E-06	8.81E-07	2.66E-06	1.42E-05	5.78E-07
Ionizing radiation	kBq U235 eq	1.13E-02	2.78E-03	5.56E-04	6.87E-04	1.13E-02	3.63E-04
Photochemical ozone formation	kg NMVOC eq	8.66E-05	7.11E-05	4.72E-06	9.06E-05	8.64E-05	3.47E-06
Acidification	molc H+ eq	2.01E-04	1.15E-04	1.08E-05	7.31E-05	2.00E-04	7.21E-06
Terrestrial eutrophication	molc N eq	3.04E-04	2.17E-04	1.71E-05	3.10E-04	3.03E-04	1.23E-05
Freshwater eutrophication	kg P eq	4.16E-06	2.76E-06	2.25E-07	2.88E-07	4.10E-06	1.60E-07
Marine eutrophication	kg N eq	2.74E-05	1.82E-05	1.49E-06	2.82E-05	2.73E-05	1.10E-06
Freshwater ecotoxicity	CTUe	9.33E-03	1.31E-02	1.33E-03	2.31E-03	9.16E-03	5.59E-04
Land use	kg C deficit	1.46E-02	2.18E-02	9.65E-04	1.09E-02	1.46E-02	7.62E-03
Water depletion	m3 water eq	2.53E-04	3.20E-04	1.27E-05	1.70E-05	2.50E-04	8.39E-06
Abiotic resource depletion	kg Sb eq	1.89E-07	4.43E-07	3.21E-08	4.37E-08	1.83E-07	9.96E-09

Cumulative Exergy demand

Figure 30 shows the comparison of the cumulative exergy demand off different cooling options in MJ-eq per MJ of cooling provided, split into sub-categories of exergy. The cooling with a waste-heat driven absorption chiller and with groundwater reach extremely low results, whereas the smaller absorption chiller (50kW) with heat from cogeneration has lower values. The larger absorption chiller (100kW) with heat from cogeneration (generic data) reaches similar values compared to the reference. All absolute values are given in Table 23.

The cooling with groundwater and with the waste heat driven absorption chiller have the lowest cumulative exergy demands. If the absorption chiller from Parker is driven by heat from a cogeneration unit, the cumulative exergy demand is almost half the impact compared to the reference cooling with an electric chiller. The cooling of the larger absorption chiller (100kW) driven by heat from a cogeneration plant (generic data) is in the same range as the ice water from electrical chiller.

The main contribution to the total cumulative exergy demand stems from the sub-categories non-renewable, fossil and non-renewable, nuclear. The other sub-categories only contribute little. In the sub-category non-renewable, fossil, the two options that include cogeneration have higher values compared to the reference (ice water, at electrical chiller), whereas the cooling with groundwater or with a waste heat driven absorption chiller has much less. If the sub-category non-renewable, nuclear is considered, the electrical cooling has higher values since European electricity partly stems from nuclear power plants.

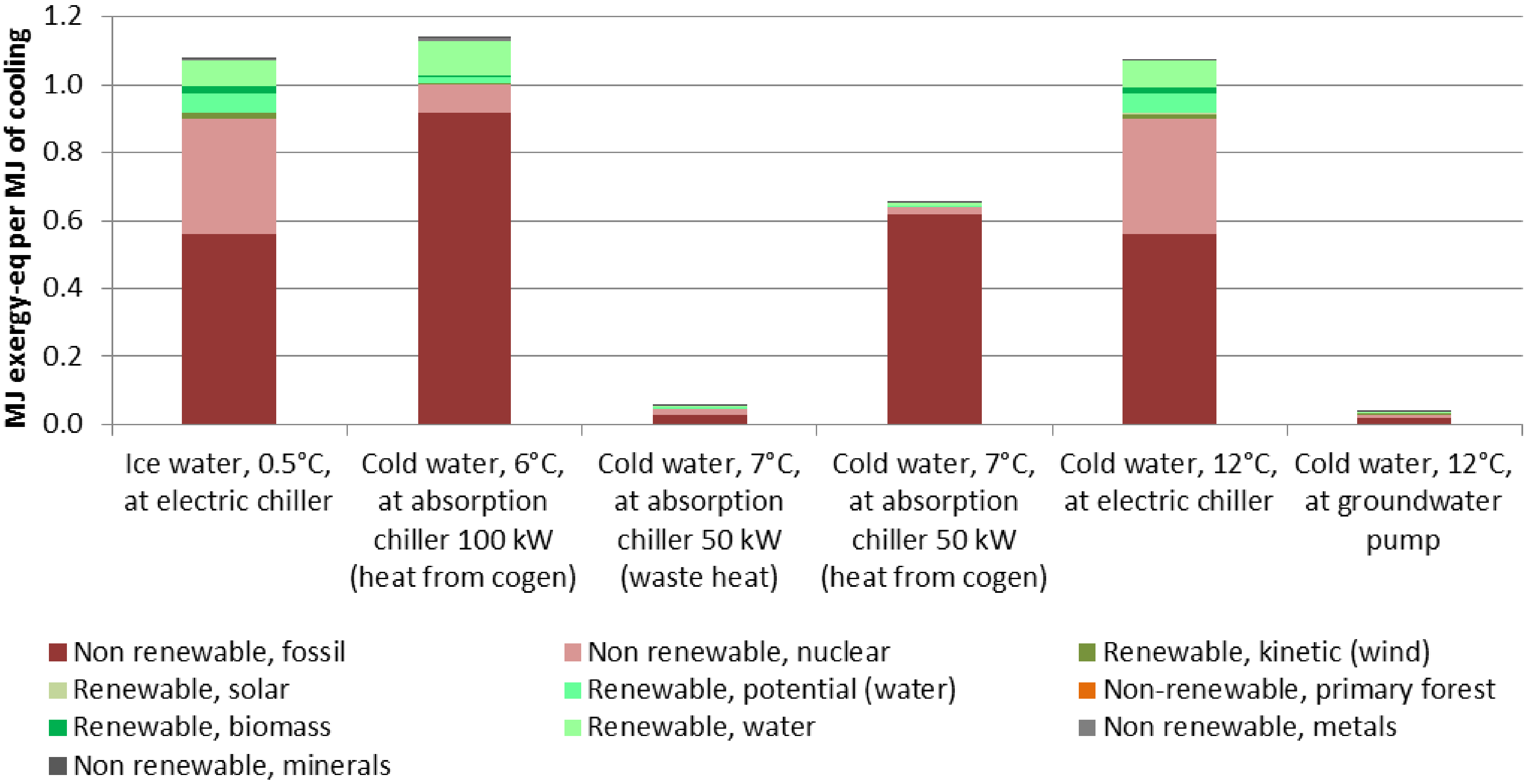

Figure 30 Total exergy demand in MJ-eq per MJ of cooling delivered. Non-renewable exergy inputs are depicted in red and grey (grey for minerals and metals), renewable exergy is depicted in green. For the values used in this graph, please refer to the table below.

Table 23 Cumulative exergy demand of different types of cooling given in absolute values (MJ-eq per MJ of heat supplied). The shades show the importance of the exergy sub-categories within each cooling process. (E.g. the higher the value of each exergy sub-category compared to the other subcategories within the process cold water, at absorption chiller, the greyer the shade).

Impact category	Unit	Ice water, 0.5°C, at electric chiller	Cold water, 6°C, at absorption chiller 100 kW (heat from cogen)	Cold water, 7°C, at absorption chiller 50 kW (waste heat)	Cold water, 7°C, at absorption chiller 50 kW (heat from cogen)	Cold water, 12°C, at electric chiller	Cold water, 12°C, at groundwater pump
Non renewable, fossil	MJ	5.61E-01	9.18E-01	2.91E-02	6.19E-01	5.60E-01	1.94E-02
Non renewable, nuclear	MJ	3.39E-01	8.35E-02	1.66E-02	2.06E-02	3.39E-01	1.09E-02
Renewable, kinetic (wind)	MJ	1.49E-02	3.53E-03	7.30E-04	9.06E-04	1.49E-02	4.67E-04
Renewable, solar	MJ	7.42E-04	1.76E-04	3.63E-05	4.47E-05	7.42E-04	2.33E-05
Renewable, potential (water)	MJ	5.96E-02	1.83E-02	3.21E-03	4.71E-03	5.96E-02	1.95E-03
Non-renewable, primary forest	MJ	2.62E-07	1.25E-06	1.56E-08	5.23E-07	2.60E-07	1.14E-08
Renewable, biomass	MJ	1.92E-02	5.04E-03	9.56E-04	1.21E-03	1.92E-02	6.10E-04
Renewable, water	MJ	7.80E-02	9.88E-02	3.91E-03	5.23E-03	7.73E-02	2.59E-03
Non renewable, metals	MJ	1.32E-03	9.78E-03	4.77E-04	8.82E-04	1.12E-03	2.27E-04
Non renewable, minerals	MJ	1.44E-04	3.03E-04	1.13E-05	1.09E-04	1.43E-04	6.83E-05
Cumulative exergy demand	**MJ**	**1.07**	**1.14**	**0.06**	**0.65**	**1.07**	**0.04**

4.5.2. Analysis of ice water at electrical chiller

Ice water and cold water at electrical chiller are modelled in a very similar way. In the comparison (see Figure 29 in Chapter 4.5.1) of the cooling options, the difference between the cold water and the ice water per MJ of cooling delivered is very small. Therefore, only the ice water is analyzed in detail here.

Electricity input dominates all impact categories except ozone depletion (see Figure 31). For this impact category, losses of refrigerants at the electrical chiller and also the refrigerant emissions during the production of refrigerants (named “refrigerant inputs”) have the main impact. The amount of losses is assessed based on similar processes and not measured at a dairy. So for the category ozone depletion, the amount of refrigerants lost and the type of refrigerant used decide upon the total impact.

For climate change, the fossil input for electricity production has the main input. Since some refrigerants also have an impact on climate change, the losses of these refrigerants also have an impact of more about 16 percent.

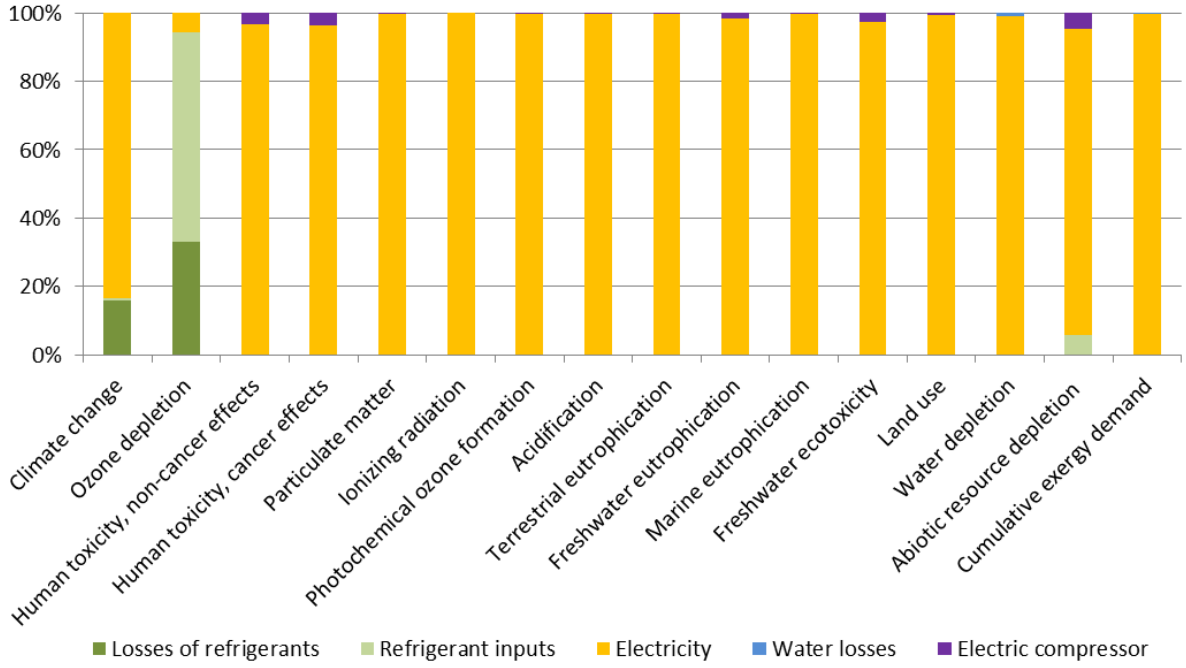

Figure 31 ILCD impact categories and cumulative exergy demand: Analysis of cooling of ice water at electric compressor.

4.5.3. Analysis of cold water from groundwater

To use groundwater for cooling, a pump station and electricity is needed. The size of the pump station depends on local circumstances and only rough estimations were available for this study. The amount of electricity that is needed to pump the water depends on the groundwater level that is very variable on a local scale (see sensitivity analysis in Chapter

6.2). Here, the groundwater level at Oberhausen is used (14m below ground[11], 12° us[12]).

Electricity for pumping is the main contributor to the total impact of cooling in eleven impact categories (Amongst others climate change and cumulative exergy demand, see Figure 32). For climate change, 84% of the impacts stem from electricity for operation and 16% from the pump station, where the input of cement is the main contributor.

In the categories human toxicity, non-cancer effect, freshwater ecotoxicity and abiotic resource depletion, the share of electricity and the pump station on total impacts are in the same range. For the impact category human toxicity, non-cancer effect, the input of steel, iron and copper for the pump station amount to over 40% of the total impact. For the freshwater ecotoxicity, around one third of total impacts stems from cast iron and steel input for the pump station. In the category abiotic resource depletion, the uranium used to produce electricity as well as copper (85% used for the pump station) have the main impact.

The pump station is the highest share in the categories human toxicity, cancer effects and land use. In the category human toxicity, cancer effects, the steel and cast iron used for the pump station contribute most. For land use, the occupation of land by the pump itself is responsible for about 90% of the impacts.

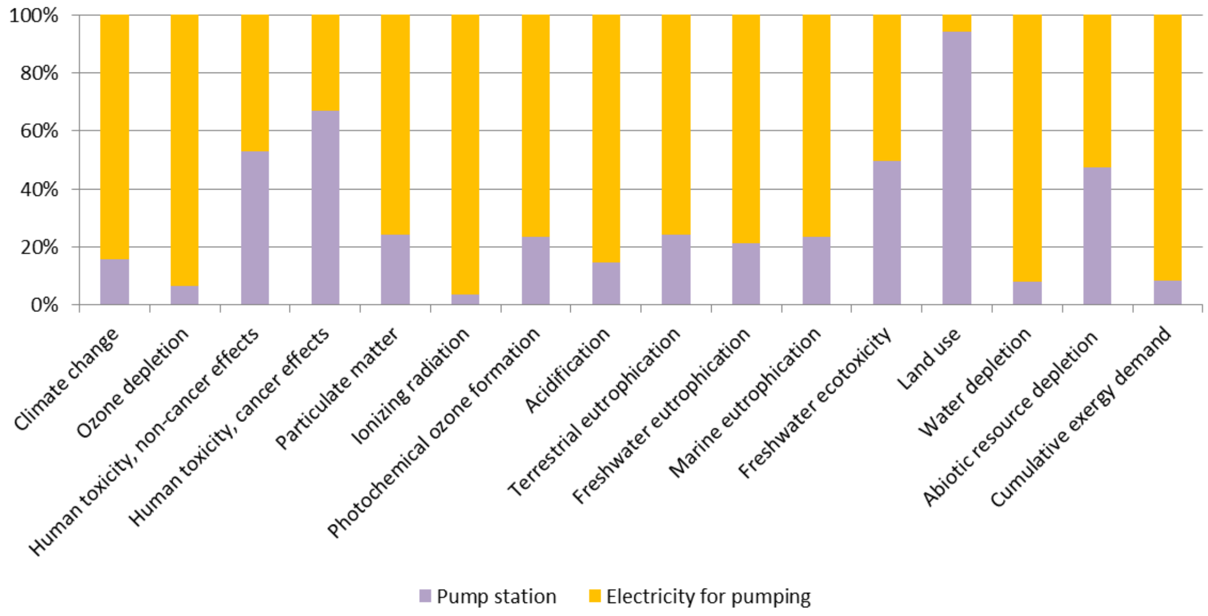

Figure 32 ILDC impact categories and cumulative exergy demand: Analysis of cooling with groundwater

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[11] Zak, Uwe: "SERVICE-SERIE ÖKOLOGIE: Mit Grundwasser verantwortungsvoll umgehen" from 28.06.2013, 08:00, visited on 10.03.2016, 14:00: http://www.derwesten.de/staedte/nachrichten-aus-moers-kamp-lintfort-neukirchen-vluyn-rheurdt-und-issum/mit-grundwasser-verantwortungsvoll-umgehen-id8123402.html

[12] RWW: „Trinkwasseranalyse“ from 30.11.2013, visited on 10.3.2016, 14:00. http://www.rww.de/fileadmin/pdf-Dateien/analyse_dorsten.pdf

The amount of cooling energy that can be retrieved from the groundwater depends on the groundwater temperature. This influences the comparison to other technologies (see sensitivity analysis in Chapter 6.2).

4.5.4. Analysis of cold water from absorption chiller using waste heat

The main environmental impact in the cooling with the absorption chiller stems from electricity used during operation in all impact categories except for human toxicity, cancer effects, freshwater ecotoxicity and abiotic resource depletion (see Figure 33). In these categories, the infrastructure respectively the absorption chiller has the main influence. For human toxicity, non-cancer effects, the absorption chiller production and the electricity each contribute around half of total impacts. The transport of the absorption chiller from production to final destination is negligible (0-1% of total impact).

For human toxicity, cancer effects, the production of the absorption chiller and the electricity each contribute about half to the total amount. The production of ferrochromium used for the chiller lead to the emissions of chromium into water (mainly into groundwater) and into air which are important potential contributors to the effect on cancer. This effect could be reduced by decreasing the amount of stainless steel used for the chiller or by choosing steel production companies that work on reducing verifiably their chromium emissions into air and water.

For the resource depletion, the use of ferronickel for the production of stainless steel has the main impact (more than 50%).

Therefore, the environmental impact of the absorption chiller can be reduced best if the efficiency of the cooling and the efficiency of the pump is increased.

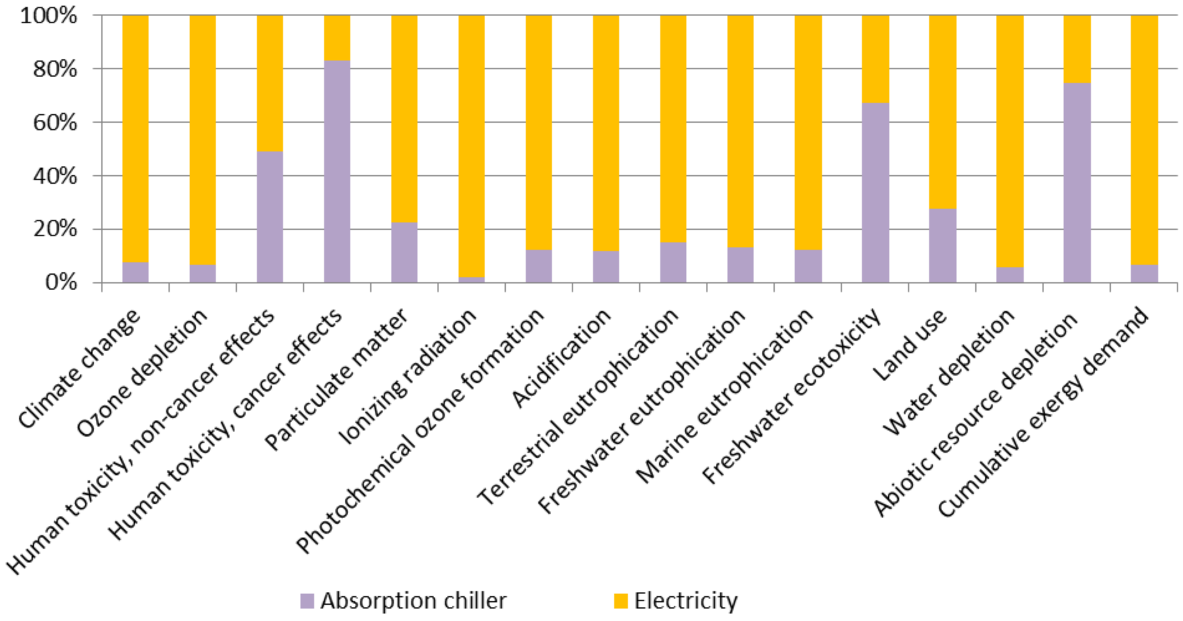

Figure 33 ILDC impact categories and cumulative exergy demand: Main contributors to the environmental impacts of cold water at absorption chiller (driven by waste heat). Electricity for operation and the production of the absorption chiller (including the transport of the chiller to the destination) are depicted.

When only the production of the absorption chiller is considered (The absorption chiller corresponds to the blue bars in Figure 33 respectively to Figure 34), the input of steel has the highest share of the total environmental impacts. In water resource depletion, the processing of materials (the sheet rolling of the chromium steel) has the highest impact. In the category freshwater eutrophication, the copper input leads to the highest environmental impact. The aluminum input and the zinc coating also have a visible impact on the total environmental impact of the absorption chiller.

In the impact categories human toxicity, cancer effects, freshwater ecotoxicity and abiotic resource depletion, the share of the production (incl. materials) of the absorption chiller of total impact is more than 50%, for human toxicity, non-cancer effect almost 50% (see Figure 33). In these categories, an improvement of the total environmental performance could be achieved by decreasing the impact of the production of the absorption chiller. In the other categories, an improvement of the environmental performance should focus on the electricity use for operation.

When viewing the split of the different inputs to produce the absorption chiller (Figure 34), the steel input has more than half of the share of impact in almost all impact categories. The exception is water resource depletion and freshwater eutrophication, where the production of the absorption chiller only contributes little to the total impact (5% to 15%). Therefore, the amount of steel used for the absorption chiller is an important leverage for the total impact in the three categories human toxicity, cancer effects, freshwater ecotoxicity and abiotic resource depletion.

If the efficiency of the absorption chiller can be improved, both the impact of the electricity as well as the impact of the absorption chiller per MJ of provided cooling decreases.

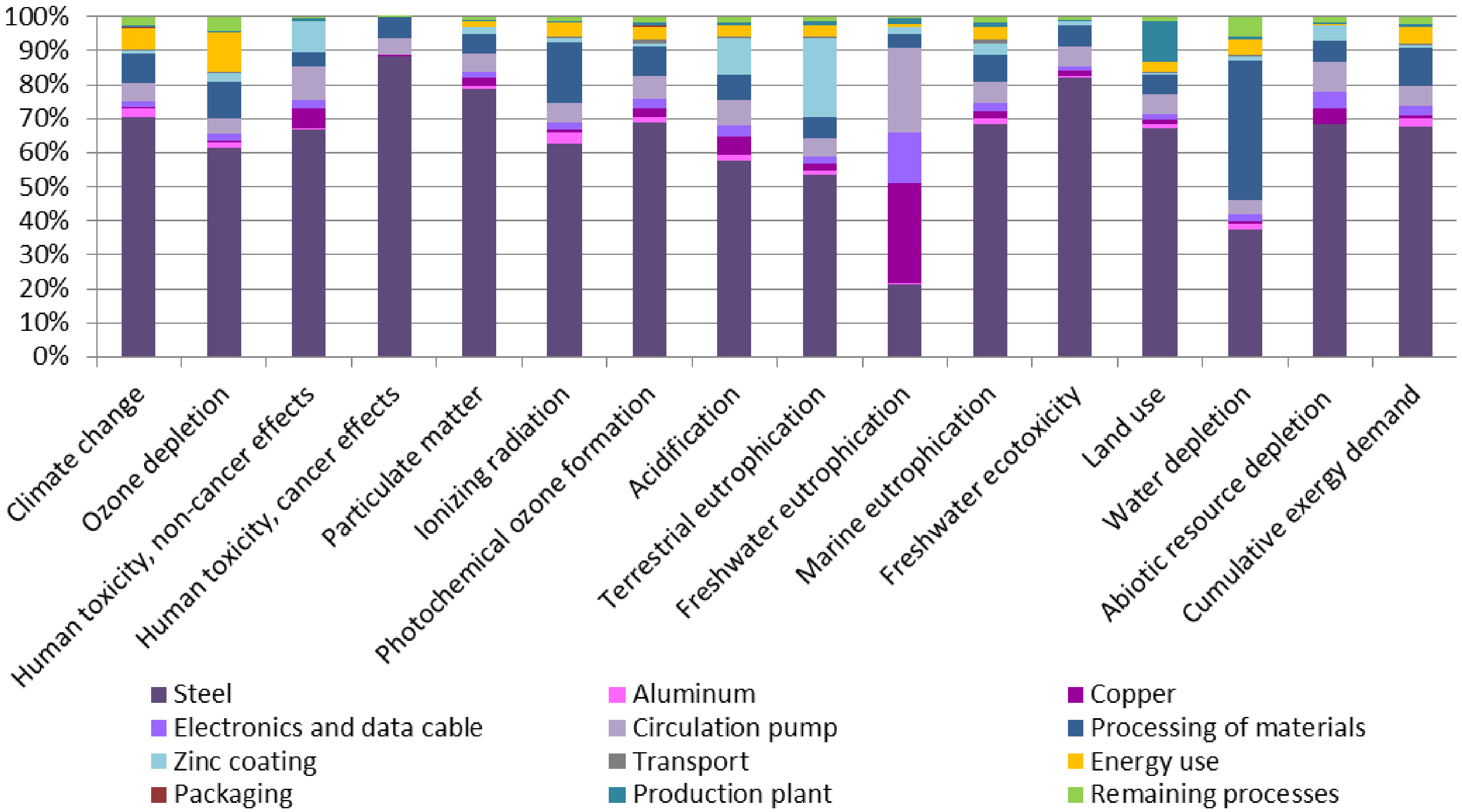

Figure 34 ILDC impact categories and cumulative exergy demand: Main contributors to the environmental impacts of the production of the absorption chiller. The group “other material” includes tube insulation, plastics included in the chiller and water use at production plant.

5. Normalization and weighting of environmental impacts

5.1. Introduction

A general problem of using the category indicators recommended by the ICLD is the interpretation of possible trade-offs between different impact categories. Often results in this analysis are not favorable for all indicators. Thus, a normalization and weighting can be applied in which it is decided which indicators are considered more or less important. Finally all environmental impacts are than summarized in one dimensionless indicator (single score).

5.1.1. Background

One option in the LCA methodology is to normalize and weight the characterized results of the impact assessment in order to facilitate the interpretation of results (International Organization for Standardization (ISO) 2006b):

- Normalization: calculating the magnitude of category indicator results relative to reference information. Often, all emissions and resource uses during one year in a certain geographical room e.g. Switzerland, Europe or worldwide caused by one person are used as a reference. But there is also the option to use an internal normalization e.g. the total emissions and resource uses of a company as a reference. The normalization factor is calculated as one divided by the reference.
- Weighting: converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices. The data prior to weighting should remain available. The weighting expresses the relative importance of different environmental indicators for the decision making. This can be based on the environmental relevance, but also on other aspects such as reliability of the indicator.

The single score is calculated by summing up the results of all category indicators multiplied with the normalization factor and multiplied with the weighting factor for each category.

5.1.2. Findings from the LCIA in this study

A detailed analysis of LCIA results for single category indicators in this study in chapter 4 reveals further insights about uncertainties and reliability of different indicators.

Today, climate change is often in the focus of public debate. So far no agreement has put into practice that really can solve this environmental problem. The models of the IPPC show that a global warming is very likely to happen in an extent that can be considered dangerous. The scenarios of 2013 show a higher global warming compared to the scenarios from 2007, showing that the problem is intensifying. Thus, this problem is considered important for the interpretation.

The assessment on the impact on the ozone depletion is based on a sound modelling of the effect. The finding is that much of the effect stems from background data and not from the newly modelled data based on questionnaires. The tendency is that gases that foster ozone depletion are already being replaced for several years by other gases. The background data does not always represent up to date information and for the most relevant emissions in gas extraction it is more than 10 years old. Therefore, this impact category does not provide much informative value. It should therefore not be given priority when analyzing the environmental impacts.

The evaluation of human toxicity impacts is often influenced by emissions of heavy metals in disposal processes. These emissions take place over several years and it is not clear if they are fully accounted for in the normalization of the ILCD.

The category particulate matter assesses the amount of particles emitted. The particles are assessed both depending on their size and their composition (i.e. sulfur dioxide emissions), but independent of the origin of these particles. The study of Kelz et al. (2010) indicates that the origin does matter: Three health effects (inflammatory responses, detection of necrosis and DNA damage) of particulate matter in vitro were analyzed. Particles from different wood combustion systems (e.g. modern pellets or wood chips boiler and an old logwood boiler) were compared to the health effect of particles from a diesel boiler. In this study, the adverse effects of the particles from modern wood combustions systems were significantly smaller than the effects of diesel particles with the same dose. It is therefore possible that the expected damage of particles from wood combustion is overestimated with the method chosen.

The category ionizing radiation reflects the use of nuclear electricity. Since the European electricity mix is used for modelling, the category mainly reflects the European electricity use with the same share of nuclear electricity. This category is therefore important if fossil based technologies are compared against technologies depending more on electricity.

The categories acidification, terrestrial eutrophication and marine eutrophication often show similar results since the emission of nitrogen oxides play a role for all these impact categories. This overlap should be considered in the interpretation.

The impact category land use does not assess the area in square meters, but assesses the changes in soil organic matter of a given area, measured in kilogram carbon deficit (kg C deficit). A factor is applied to assess the carbon deficit based on the type of land transformation and the size of the area affected. This factor is crucial for the final results: For heat provision based on wood as energy source, the area needed is higher than for fossil fuels, but the land use evaluated with this method of C deficit leads to a lower impact of the wood-based heat provision. The reason is that the factor for the transformation to a mineral extraction site is extremely higher than the factor of the transformation of an area to intensive forestry. Also, the same factor is used both for a copper extraction mine and for the extraction of crude oil, even if these two land uses have a different influence on the carbon change of the considered area. Therefore, the results of this impact category shall be used with caution.

The indicator abiotic resource depletion is influenced very much by materials which were so far not in the focus of life cycle inventories (e.g. indium). The evaluations in this study often show a huge impact by zinc uses which are also not very well followed up in the LCI. Energy resources which are very well covered in LCI data, are not relevant for this indicator under the recommended approach for characterization.

Furthermore, there are overlaps and uncertainties of different category indicators which should be considered in the interpretation.

An update of the ILCD methodology recommendations is presently under public discussion. The findings from several ongoing projects for the product environmental footprint confirm the findings of this study concerning the difficulties described above in interpreting the results with some indicators: Therefore the present proposal foresees to split the assessment for resource into an assessment of energy resources and abiotic resources, and to apply new methods for land use and water consumption (Sala et al. 2016).

5.2. Approaches used for normalization and weighting in this study

Five different approaches for normalization and weighting are applied in this project. They are described in this chapter.

5.2.1. Approach used for European PEF studies (PEF-points)

The ILCD handbook (European Commission et al. 2011) does not directly provide any guidance for these two steps. But the JRC did further work on this issue in the framework of the product environmental footprint (PEF).

The factors for European and Global normalization are calculated by Benini et al. (2014) for the impact categories according to the ILCD recommendations. They are shown in Table 26.

Some results of this normalization in the study by Benini et al. (2014) are difficult to understand. Energy resources which are very well covered in LCI data, are not relevant for this indicator and account for less than 0.5% of the total impacts. The normalization according to ILCD shows the highest impact from strontium which is so far not considered in none of the LCI databases. The high relevance of strontium is not reflected in the public debate about resource uses and not easy to understand. Second most important is silver, which might also be difficult to follow up due to small amounts mainly used in electronics. Thus background data for this category indicator seem to be quite uncertain.

The weighting factors in SimaPro are based on European Commission (2016). They are used in the PEF (product environmental footprint) studies. It is stated that as a baseline approach, all impact categories shall receive the same weight. This approach does not really solve the issue of weighting. Instead, the arbitrary decision is taken that all types of impacts are considered to have the exactly same importance.

The PEF studies point out several problems related to this approach. For some of which improvement options are already discussed (Sala et al. 2016). Acknowledging the known problems the following disclaimer is recommended in the PEF studies:

Disclaimer

Within the Environmental Footprint (EF) pilot phase normalization and equal weighting were foreseen to be used in the EF screenings to identify the most relevant impact categories. The use normalization and weighting for this purpose remains the objective for the EF pilots and beyond. However, currently PEF screening results after the normalization and equal weighing present some inconsistencies stemming from errors at various levels of the assessment. Therefore, screening results after normalization and equal weighting are not sufficiently ro-

bust to apply for product comparisons in an automatic and mandatory way in the Environmental Footprint (EF) pilots, e.g. to identify the most relevant impact categories. The interpretation of the results reflects these limitations.

To avoid potential misinterpretation and misuse of the EF screening results we highlight that the results after normalization and equal weighting, - without further error checking and possibly corrections, - are likely to overestimate or underestimate especially the relevance of the potential impacts related to the categories Human toxicity - cancer effect, Human toxicity - non-cancer effect, Ecotoxicity for aquatic fresh water, water depletion, resource depletion, ionizing radiation and land use.

5.2.2. Normalization and Weighting by LCA experts (ESU-points)

Three approaches for normalization and weighting are developed by the authors of this report and tested in this project. The approaches are based on the findings described in Chapter 5.1.2.

5.2.2.1. *Normalization*

Three approaches for normalization are tested.

One reference for the normalization is the global (GLO) emissions and resource uses per person and day (SimaPro 8.2).

The next normalization uses the environmental impacts of the daily operation of the LCA dairy model (without raw milk input) as a reference (Table 24). ISO 14044 explains this approach in Chapter 4.4.3.2.2 as follows: the reference value is the inputs and outputs in a baseline scenario, such as a given product system (International Organization for Standardization (ISO) 2006b). The operation of the dairy without the raw milk input is the main focus of the SUSMILK project.

Thus, the single score derived with this method for the environmental impacts of the daily operation is 1. The focus is laid on the improvement of this daily operation and each score below 1 for the daily operation means an improvement compared to the present situation.

The environmental impacts of the dairy operation are quite different if the raw milk supply is included in the assessment (see Figure 5). In order to check the reliability of the approach, a third approach is used for the normalization reference. In this approach the daily operation including the raw milk supply is used as a reference.

All three sets of normalization factors are shown in Table 26.

5.2.2.2. *Weighting*

One approach for weighting has been developed by the authors of this study. The aim was to take into account both the reliability and robustness of the data and the LCIA methods as well as the focus of the SUSMILK project concerning these impacts.

Six different aspects have been identified in the course of the project to be critical for the interpretation of the results. These aspects are taken here into account for the weighting of different category indicators by the authors of this study (Table 24). For each of these aspects and for each category indicator a factor between 1 and zero is estimated. The overall score is derived by multiplying the factor for each aspect. The weighting factor is then calculated by dividing the overall score through the sum of all overall scores.

The robustness of the European normalization data considers the information available from PEF projects and own evaluations. It is not taken into account for the ESU expert weighting as here the global normalization data is chosen.

The reliability of LCI background data considers if background data used in this analysis are reliable for the assessment of the single environmental problem. The estimation is based on several discussions made in Chapter 4. Thus, e.g. the factor for ozone depletion is set to only 20% as background data for this aspect seem to be outdated.

The reliability is also estimated for foreground data used in the LCI based on the extent this data influences the results for a certain indicator. Impact categories for which no direct emissions or resource uses are reported for are considered less relevant than aspects for which there are direct emissions or resource uses in the foreground data.

The reliability for the LCIA methods considers the rating made for the “Rec Level” (European Commission et al. 2011: Table 1). A factor of 100% equals a Rec Level of I, while40% is given for category III.

The aspect concerning the overlap of the LCI considers that some category indicators show very similar results because they are dominated by the same emissions in the life cycle assessment. In order to reduce multiple counting of the same emission, these indicators are given less weight.

Finally, the focus of the SUSMILK project is taken into account as well. A main focus according to the description of work is laid on the reduction of energy and water uses in the dairy. Thus less relevance is given to environmental problems that are not directly related to these energy and water uses.

As a result of this approach, highest weights are given to the problems of climate change, particulate matter formation, ozone formation and eutrophication and water use. Less important is e.g. ozone depletion as it is considered to be based on unreliable data and it is not in the focus of the project.

The indicator is called “ESU-points”.

Table 24 Weighting approach developed by the authors of this study (ESU-points)

		Robustness European normalization	Reliability, LCI, background	Reliability, LCI, foreground	Reliability, LCIA	Overlap, LCI	Focus SUSMILK	Overall score	**Weighting, ESU**
Climate change	kg CO2 eq	100%	100%	100%	100%	100%	100%	100.0%	**23.0%**
Ozone depletion	kg CFC-11 eq	60%	20%	80%	100%	100%	50%	8.0%	**1.8%**
Human toxicity, non-cancer effects	CTUh	20%	50%	80%	60%	100%	50%	12.0%	**2.8%**
Human toxicity, cancer effects	CTUh	20%	50%	80%	60%	100%	50%	12.0%	**2.8%**
Particulate matter	kg PM2.5 eq	100%	90%	80%	100%	100%	50%	36.0%	**8.3%**
Ionizing radiation	kBq U235 eq	60%	90%	100%	80%	100%	50%	36.0%	**8.3%**
Photochemical ozone formation	kg NMVOC eq	60%	100%	100%	80%	100%	50%	40.0%	**9.2%**
Acidification	molc H+ eq	80%	100%	100%	80%	33%	50%	13.3%	**3.1%**
Terrestrial eutrophication	molc N eq	60%	100%	100%	80%	33%	50%	13.3%	**3.1%**
Freshwater eutrophication	kg P eq	40%	100%	100%	80%	100%	50%	40.0%	**9.2%**
Marine eutrophication	kg N eq	40%	100%	100%	80%	33%	50%	13.3%	**3.1%**
Freshwater ecotoxicity	CTUe	20%	100%	100%	60%	100%	50%	30.0%	**6.9%**
Land use	kg C deficit	60%	90%	100%	40%	100%	50%	18.0%	**4.1%**
Water depletion	m3 water eq	40%	80%	100%	40%	100%	100%	32.0%	**7.4%**
Abiotic resource depletion	kg Sb eq	20%	30%	80%	80%	50%	50%	4.8%	**1.1%**
Cumulative exergy demand	MJ-eq	100%	80%	80%	80%	50%	100%	25.6%	**5.9%**

5.2.3. Normalization and Weighting by SUSMILK partners (SUSMILK-points)

A first discussion of LCA results shown in this study with the SUSMILK partners further highlighted the different points of view which can be taken in the assessment of detailed LCA results. Statements in the discussion were quite different and they were also partly influenced by intended outcomes of the study. In order to take the different concerns into account, all project partners have been asked to submit and justify their point of view concerning normalization and weighting with the following question:

"Please add your weighting figure in column B and give reasoning for the weighting choice in column C. The value must be between the minimum (1%) and maximum (85%) weight. The total must add up to 100%. You are free to assign a weight for the relevance of each of the 16 environmental impact categories. Choose the weight according to the way you would consider the categories for decision making. All impact categories are described in the draft Del 7.3, chapter 3.2.7 (Table 5 and 6)."

In total 12 answers have been received. Some of the project partners who answered have a detailed knowledge on LCA while others are more technical experts on technologies and have a lower knowledge of environmental issues. Table 25 presents the results used in this approach. Results of this approach are presented as SUSMILK-points.

Table 25 Average of weighting scores according to a questionnaire sent to all partners in the SUSMILK project. Further information on minimum (MIN), median and maximum (MAX) weights. Votes per normalization approach.

Impact category	**Average**	Min	Median	Median, 100%	Max
Climate change	39.67%	10.0%	31.5%	40.0%	85.0%
Ozone depletion	3.83%	1.0%	3.5%	4.4%	10.0%
Human toxicity, non-cancer effects	3.63%	1.0%	1.5%	1.9%	15.0%
Human toxicity, cancer effects	4.46%	1.0%	1.8%	2.2%	14.0%
Particulate matter	6.17%	1.0%	5.0%	6.3%	20.0%
Ionizing radiation	4.08%	1.0%	4.0%	5.1%	8.0%
Photochemical ozone formation	3.46%	1.0%	3.0%	3.8%	10.0%
Acidification	3.25%	1.0%	2.0%	2.5%	10.0%
Terrestrial eutrophication	2.88%	1.0%	2.0%	2.5%	10.0%
Freshwater eutrophication	3.29%	1.0%	2.3%	2.9%	10.0%
Marine eutrophication	2.63%	1.0%	2.3%	2.9%	6.0%
Freshwater ecotoxicity	3.25%	1.0%	2.0%	2.5%	8.0%
Land use	4.58%	1.0%	4.5%	5.7%	10.0%
Water depletion	6.33%	1.0%	5.5%	7.0%	20.0%
Abiotic resource depletion	2.33%	1.0%	2.0%	2.5%	8.0%
Cumulative exergy demand	6.17%	1.0%	6.0%	7.6%	11.0%
Total	**100.0%**	**25.0%**	**78.8%**	**100.0%**	**255.0%**
Preferred normalization	Votes				
1) Operation of the dairy without raw milk production	2.33				
2) Operation of the dairy including raw milk production	2.33				
3) Total European emissions	6.33				

5.2.4. Summary of normalization factors

Table 26 shows the different set of normalization factors used in this study. The European normalization is based on Benini et al. (2014). It refers to the annual emissions and resource uses per capita in Europe. The figures for daily operation with and without raw milk input are directly calculated in this study (chapter 4.2). They refer to the daily operation of the generic dairy.

Table 26 Normalization factors used in this study

Impact category	Unit	Global emission per year and capita	**Normalization, GLO**	European emission per year and capita	**Normalization, EU**	Daily operation, Milk included	**Normalization, Milk included**	Daily operation, Milk excluded	**Normalization, Milk excluded**
Climate change	kg CO2 eq	6.89E+03	**1.45E-04**	9.09E+03	**1.10E-04**	5.64E+05	**1.77E-06**	1.12E+05	**8.93E-06**
Ozone depletion	kg CFC-11 eq	3.76E-02	**2.66E+01**	2.16E-02	**4.63E+01**	2.87E-02	**3.49E+01**	1.42E-02	**7.05E+01**
Human toxicity, non-cancer effects	CTUh	1.95E-04	**5.12E+03**	5.33E-04	**1.88E+03**	-4.55E-01	**-2.20E+00**	7.29E-03	**1.37E+02**
Human toxicity, cancer effects	CTUh	6.33E-05	**1.58E+04**	3.69E-05	**2.71E+04**	1.12E-02	**8.90E+01**	1.07E-03	**9.31E+02**
Particulate matter	kg PM2.5 eq	1.67E+00	**5.98E-01**	3.80E+00	**2.63E-01**	2.80E+02	**3.58E-03**	3.51E+01	**2.85E-02**
Ionizing radiation	kBq U235 eq	1.32E+03	**7.59E-04**	1.13E+03	**8.85E-04**	3.46E+04	**2.89E-05**	1.02E+04	**9.84E-05**
Photochemical ozone formation	kg NMVOC eq	5.67E+01	**1.76E-02**	3.17E+01	**3.15E-02**	1.21E+03	**8.28E-04**	3.19E+02	**3.14E-03**
Acidification	molc H+ eq	4.97E+01	**2.01E-02**	4.74E+01	**2.11E-02**	8.47E+03	**1.18E-04**	4.58E+02	**2.18E-03**
Terrestrial eutrophication	molc N eq	1.15E+02	**8.69E-03**	1.76E+02	**5.68E-03**	3.63E+04	**2.76E-05**	1.42E+03	**7.04E-04**
Freshwater eutrophication	kg P eq	2.90E-01	**3.45E+00**	1.48E+00	**6.76E-01**	6.80E+01	**1.47E-02**	1.11E+01	**9.02E-02**
Marine eutrophication	kg N eq	1.40E+01	**7.13E-02**	1.69E+01	**5.92E-02**	1.87E+03	**5.36E-04**	2.31E+02	**4.34E-03**
Freshwater ecotoxicity	CTUe	6.51E+03	**1.54E-04**	8.77E+03	**1.14E-04**	4.97E+05	**2.01E-06**	4.07E+04	**2.46E-05**
Land use	kg C deficit	5.62E+04	**1.78E-05**	7.46E+04	**1.34E-05**	1.37E+07	**7.30E-08**	2.35E+05	**4.26E-06**
Water depletion	m3 water eq	*8.13E+01*	**1.23E-02**	8.13E+01	**1.23E-02**	1.04E+03	**9.61E-04**	4.98E+02	**2.01E-03**
Abiotic resource depletion	kg Sb eq	6.94E-02	**1.44E+01**	1.01E-01	**9.90E+00**	2.93E+00	**3.41E-01**	4.50E-01	**2.22E+00**
Cumulative exergy demand	MJ-eq	61'821	**1.62E-05**	9.20E+04	**1.09E-05**	1.92E+07	**5.22E-08**	2.38E+06	**4.21E-07**

5.2.5. Summary of weighting factors

Table 27 summarizes the different set of weighting factors used in this study and described in the previous chapters.

Table 27 Weighting factors used in this study

		Weighting, ESU	**Weighting, SUSMILK**	**Weighting, PEF**
Climate change	kg CO2 eq	**23.0%**	**39.7%**	**6.7%**
Ozone depletion	kg CFC-11 eq	**1.8%**	**3.8%**	**6.7%**
Human toxicity, non-cancer effects	CTUh	**2.8%**	**3.6%**	**6.7%**
Human toxicity, cancer effects	CTUh	**2.8%**	**4.5%**	**6.7%**
Particulate matter	kg PM2.5 eq	**8.3%**	**6.2%**	**6.7%**
Ionizing radiation	kBq U235 eq	**8.3%**	**4.1%**	**6.7%**
Photochemical ozone formation	kg NMVOC eq	**9.2%**	**3.5%**	**6.7%**
Acidification	molc H+ eq	**3.1%**	**3.3%**	**6.7%**
Terrestrial eutrophication	molc N eq	**3.1%**	**2.9%**	**6.7%**
Freshwater eutrophication	kg P eq	**9.2%**	**3.3%**	**6.7%**
Marine eutrophication	kg N eq	**3.1%**	**2.6%**	**6.7%**
Freshwater ecotoxicity	CTUe	**6.9%**	**3.3%**	**6.7%**
Land use	kg C deficit	**4.1%**	**4.6%**	**6.7%**
Water depletion	m3 water eq	**7.4%**	**6.3%**	**6.7%**
Abiotic resource depletion	kg Sb eq	**1.1%**	**2.3%**	**6.7%**
Cumulative exergy demand	MJ-eq	**5.9%**	**6.2%**	**0.0%**

5.3. Results

In this chapter results for normalization and weighting of environmental impacts of different improvement options are shown and discussed. A detailed analysis of single impact categories can be found in chapter 4.

The last step for this is the calculation of the single score by multiplying the normalization factor and the weighting factor presented in the previous chapter. This final factor can be multiplied with the impact assessment results for each single category indicator in order to get the final single score result.

5.3.1. Daily dairy operation

Figure 35 shows the share of points derived with different normalization and weighting approaches for the daily operation of the dairy.

The PEF-points show a very high negative importance of non-cancer human toxicity issues if raw milk is included (see discussion on page 23). If it is excluded cancer effects become more dominant. Most important are chromium emissions in the life cycle mainly from disposal of slag in the production of iron. Negative values for the operation with raw milk input are due to uptake of heavy metals in fodder production. Freshwater ecotoxicity is influenced by some heavy metal emissions in the life cycle. In general it can be said that the PEF method highlights problems for the dairy operation which do not play such an important role in the public debate.

The share of ESU-points for the daily operation of the dairy each single category indicators equals by definition the weighting given in Table 24 if it is calculated for the normalization reference (ESU, milk included / milk included and ESU, milk excluded / milk excluded).

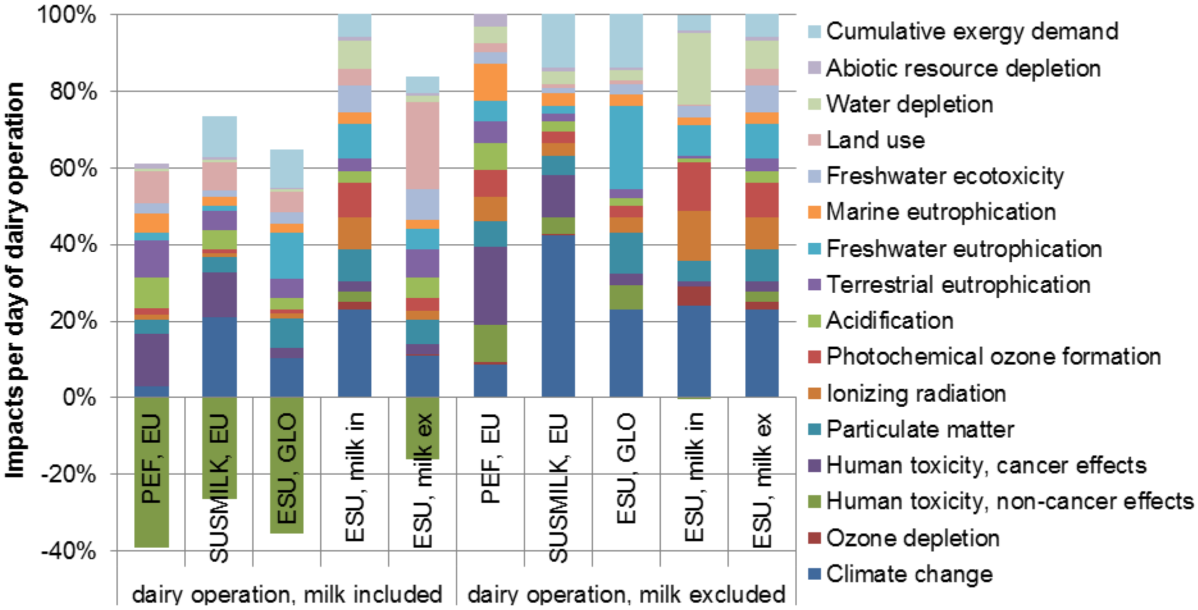

Figure 35 Share of impact categories in different single score approaches for the daily operation of the dairy.

5.3.2. Heat supply

5.3.2.1. *Improvement options*

Different options for the heat supply are compared in Figure 36 with the reference case of a heat provision with a natural gas boiler. The light fuel oil option is excluded as it always has higher impacts and stretches the axis of the figure.

For the PEF approach, several types of environmental impacts are relevant due to the equal weighting. Using the pellet boiler and cogeneration with wood has higher impacts than the reference case. The high impacts of the pellet boiler are driven by the particulate matter emissions. The large solar system on open ground is only a bit lower than the reference since it uses much land resources. The best options are cogeneration with natural gas (motor) and the gas-engine driven heat pump.

This picture changes if the weighting according to the judgement of SUSMILK partners is taken where high priority is given to climate change. With this, all improvement options lead to a reduction compared to the reference case of a natural gas boiler. The best score is calculated for the large solar system on flat roof operated with low temperatures assuming low losses within the system (see Chapter 4.3.6 for details).

With the approach developed by the LCA experts at ESU and using the daily operation without raw milk input for normalization, the following insights can be gained: The pellet boiler has higher impacts than the reference case. The high impacts of the pellet boiler are driven by the particulate matter emissions. The impact of the large solar system on open ground is twice as much as the large solar system on flat roof. The use of land resources for the large solar system on open ground is responsible for more than half the impact. The best options are the large solar system on flat roof, followed by cogeneration with natural gas (motor) and the gas-engine driven heat pump.

With changing the normalization reference to including the raw milk some important differences are visible. The impacts of land use are much smaller for the large solar system because the reference for land use is much higher when raw milk is included. Also non-cancer human toxicity effects are getting less importance. On the other side, climate change and abiotic resource depletion are getting a higher share in total impacts of several options. But the overall interpretation of results is not influenced much by these differences. Only for the pellet boiler datasets the interpretation changes, since both pellet boilers have lower impacts than the reference case. The impacts of the pellet boiler boilers are driven by the high particulate matter emissions compared to natural gas. The best options are the same as with the normalization with operation excluding raw milk.

Thus, in conclusion it can be said that the cogeneration with natural gas (motor and turbine) and the gas-engine driven heat pump as well as low temperature solar collector systems can be recommended under all ideas of normalization and weighting.

For the results for the solar systems, caution has to be used, since solar systems cannot be used stand-alone and thus the environmental impact of the additional heat source used is crucial. Additionally, the evaluation of solar systems depends on many assumptions like the layout, the place of installation, the temperature of the delivered heat and the percentage of heat losses within the solar system. For the wood-based systems, certain obstacles have to be taken into account and depending on weighting and normalization they are not favorable compared to the base case of a natural gas heating. Cogeneration with wood can be considered as an option that at least in most cases leads to an improvement. A pellet boiler without particle filters cannot be recommended as an improvement to a natural gas boiler. Even with a particle filter, a pellet boiler mainly leads to an improvement concerning the CO_2-emissions but is not favorable for several other impact categories.

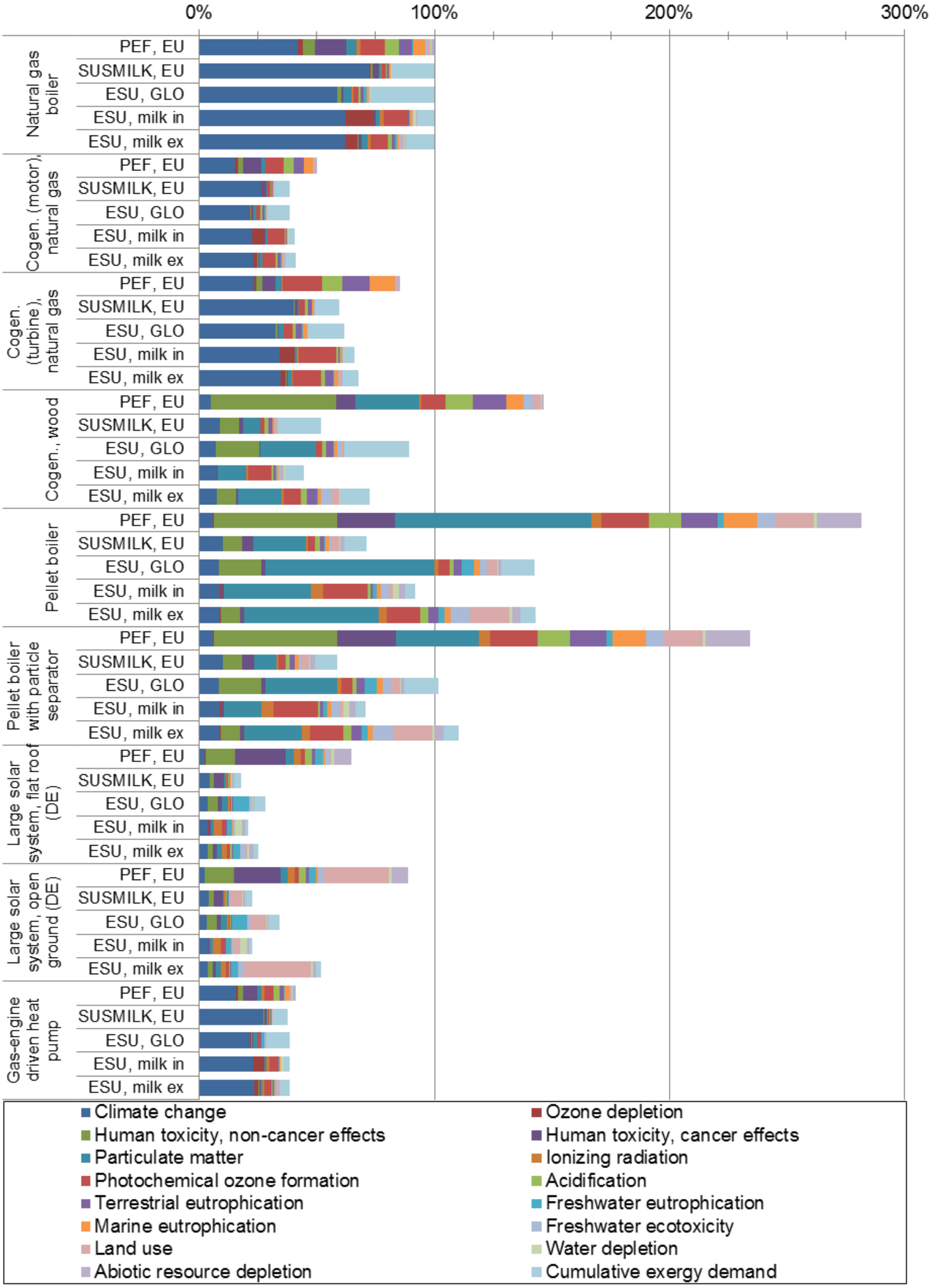

Figure 36 Comparison of heating options (per MJ) with different single score approaches, referenced to heat from a natural gas boiler

Table 28 shows the micro-points (points divided by one million) per MJ of heat for the different technologies evaluated in this study. The calculation of the points is explained in detail in Chapter 5.2.

Table 28 Total micro-points per MJ according to different normalization and weighting approaches for the different heat supply technologies

	PEF, EU	SUSMILK, EU	ESU, GLO	ESU, milk in	ESU, milk ex
Natural gas boiler	1'242	4'287	4'060	47	237
Cogen. (motor), natural gas	622	1'641	1'559	19	97
Cogen. (turbine), natural gas	1'059	2'556	2'509	31	160
Cogen., wood	1'818	2'220	3'625	21	174
Pellet boiler	3'497	3'057	5'798	43	345
Pellet boiler with particle separator	2'909	2'513	4'128	33	266
Small solar system (ES)	1'710	1'391	2'164	16	109
Large solar system, flat roof (DE)	804	769	1'144	10	60
Large solar system, open ground (DE)	1'105	971	1'385	11	125
Gas-engine driven heat pump	507	1'619	1'553	18	91

5.3.2.2. Savings due to additional installation of solar collectors and pellet boiler at Queizuar

Figure 37 shows the results of all types of heat provision installed at Queizuar: the diesel boiler already in existence, the newly installed small solar system with 60 C output temperature and the pellet boiler without particle separator. Also shown in the last line is the solar-pellet-system that combines 89.2% of heat from pellet boiler with 10.2% of heat from the small solar system. The solar-pellet system has higher impacts than the diesel boiler with the normalization and weighting approach of the PEF and comparable or lower impacts in the other approaches. This is due to the high share of heat provided by the pellet boiler that dominates the result. The solar system does not provide enough energy for the demand of the dairy at Queizuar. This is why the solar system is combined with both a pellet and the existing diesel boiler.

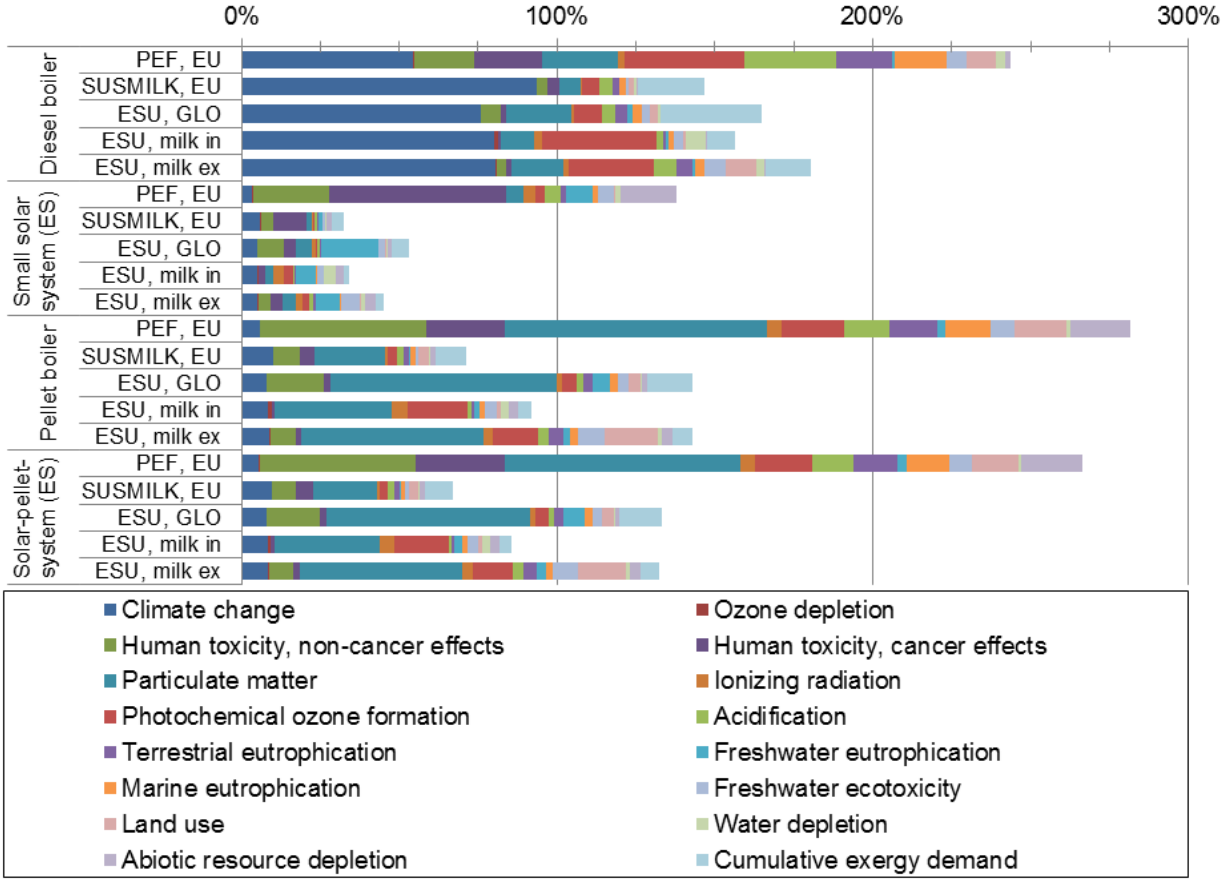

Figure 37 Comparison of heating systems at Queizuar (per MJ) with different single score approaches in relation to natural gas heating

The environmental impact of one year of operation at the dairy Queizuar before and after the installation of the solar collectors and the pellet boiler is calculated. The diesel use[13] before (measured 3.2014-3.2015) is compared to the diesel use after (measured 5.2015-5.2016), additional environmental impacts due to the materials needed for the solar collectors (30 years life time assumed) and the impact of the pellets[14] burned. Since Queizuar increased the amount of milk processed, the values are referenced to one kilogram of milk processed. The data shows that the heat demand per kg of milk processed was reduced by 10 percent. The reduction in heat demand, together with the integration of the solar-pellet system, lead to a reduction of 21% for climate change. Also in the many other impact categories, a decrease of environmental impacts resulted. In the categories abiotic resource depletion and human toxicity, non-cancer effects, an increase of environmental impact resulted. About 1% of the energy stems from the solar system, about 11% from the pellet boiler and the rest from the diesel boiler.

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[13] Data on diesel use and liters of milk processed is provided via e-mail by Ángel Pereira Rodríguez, Queziuar on 18.5. and 22.7.2016.

[14] Data on delivered pellets (kg) and solar energy (kWh) provided via e-mail by Joachim Kalkgruber, SOLARFOCUS on 13.6.2016.

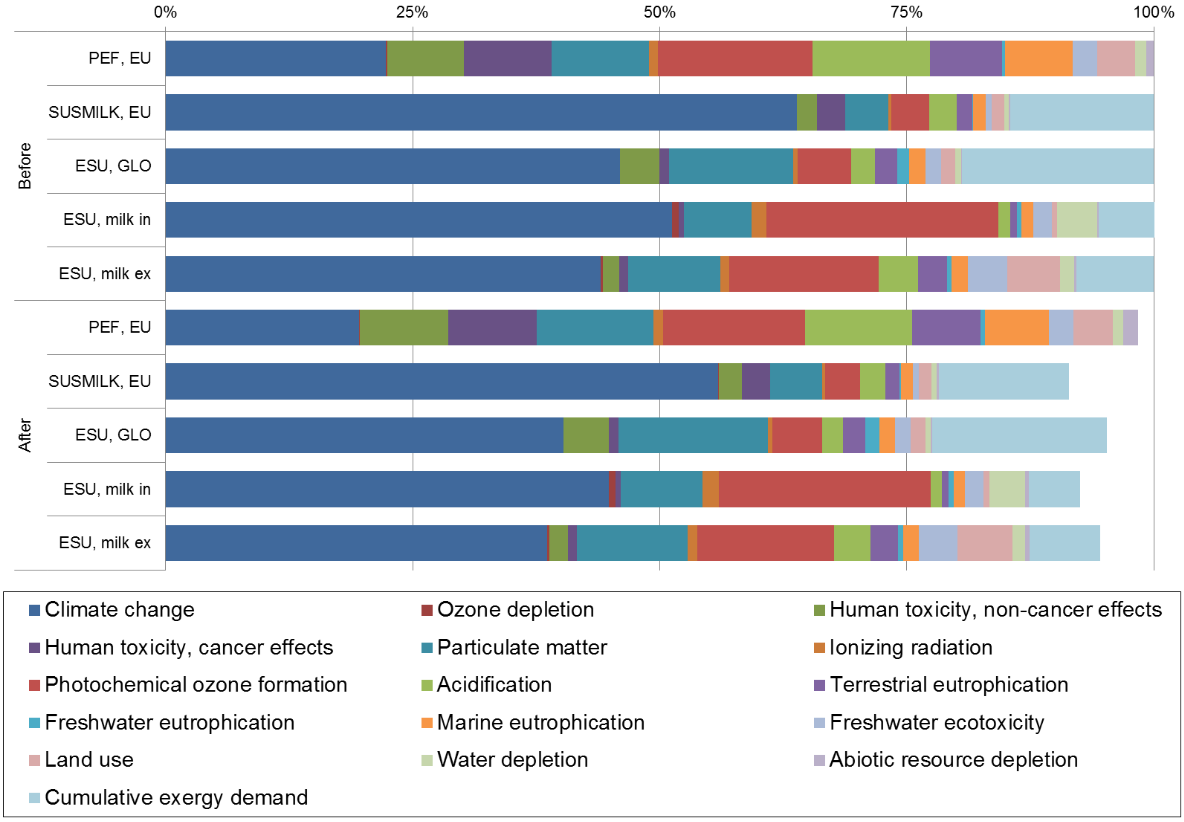

Figure 38 Environmental impacts of heat provision at the dairy Queizuar before (3.2014-3.2015) and after (5.2015-5.2016) the additional installation of solar collectors and a pellet boiler, divided by the amount of milk processed to allow the comparison.

5.3.3. Electricity supply

Figure 39 compares different options for the electricity supply with five single score methods in relation to the present European grid mix.

With all approaches, cogeneration from natural gas in motor CHP as well as the cogeneration from wood chips have overall advantages compared to the present electricity supply by the grid. From an environmental point of view, the cogeneration in a natural gas turbine has about the same or higher impacts than the average European electricity mix, especially because of much higher CO_2 and NOx emissions. Of all considered cogeneration types, only electricity form the turbine CHP with natural gas it is not an improvement option.

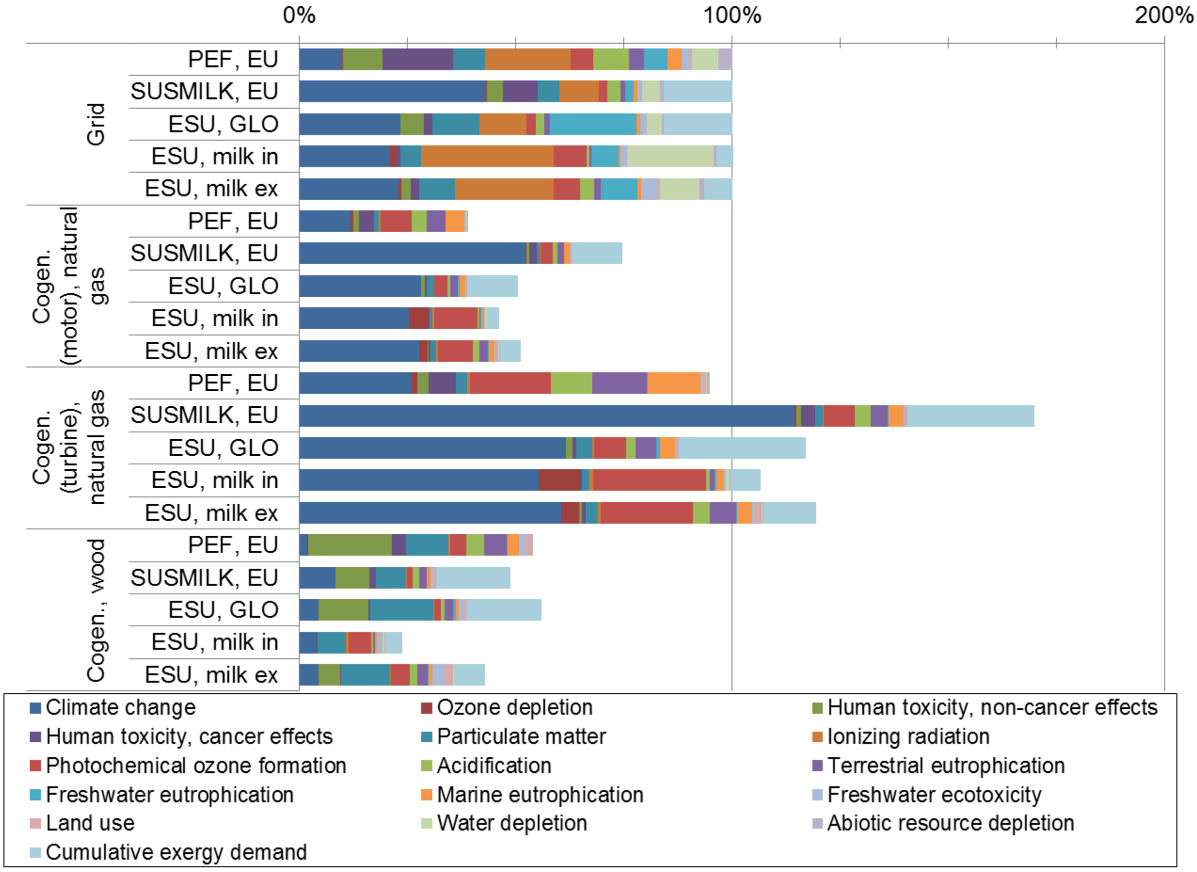

Figure 39 Comparison of electricity supply options (per kWh) with different normalization and weighting schemes

Table 29 shows the micro-points per kWh of electricity for the different technologies evaluated in this study.

Table 29 Total micro-points per kWh electricity according to different normalization and weighting approaches

	PEF, EU	SUSMILK, EU	ESU, GLO	ESU, milk in	ESU, milk ex
Grid	36'526	49'187	70'109	952	4'391
Cogen. (motor), natural gas	14'260	36'685	35'339	439	2'247
Cogen. (turbine), natural gas	34'622	83'599	82'036	1'014	5'248
Cogen., wood	19'708	24'014	39'156	223	1'883

5.3.4. Cooling

Different options for cooling are compared in Figure 40. The ice water at electric chiller is taken as a reference. It shows very similar impacts as the cold water at electric chiller if impacts are compared per MJ of cooling provided.

The absorption chiller driven by waste heat and the groundwater cooling can reduce the environmental impacts considerably. This result does not depend on the weighting and normalization approach. If the same absorption chiller is driven with heat from cogeneration, this also leads to an improvement. The calculated reduction for the absorption chiller with waste heat is lowest with the SUSMILK-points which give a high priority to climate change impacts.

As discussed before, there are large differences between the ecoinvent model for an absorption chiller with 100 kW using heat from cogeneration and the data investigated in this project. This type of chiller uses considerably more materials and thus does not lead to an unambiguous improvement compared to the present situation.

Table 30 shows the micro-points per MJ of cooling for the different technologies evaluated in this study.

Table 30 Total micro-points per MJ cooling according to different normalization and weighting approaches

	PEF, EU	SUSMILK, EU	ESU, GLO	ESU, milk in	ESU, milk ex
Ice water, 0.5°C, at electric chiller	3'613	4'321	5'842	111	446
Cold water, 6°C, at absorption chiller 100 kW (heat from cogen)	3'537	4'550	5'003	76	347
Cold water, 7°C, at absorption chiller 50 kW (waste heat)	342	303	353	5	24
Cold water, 7°C, at absorption chiller 50 kW (heat from cogen)	1'370	2'464	2'240	33	166
Cold water, 12°C, at electric chiller	3'576	4'297	5'802	111	444
Cold water, 12°C, at groundwater pump	174	172	230	3	16

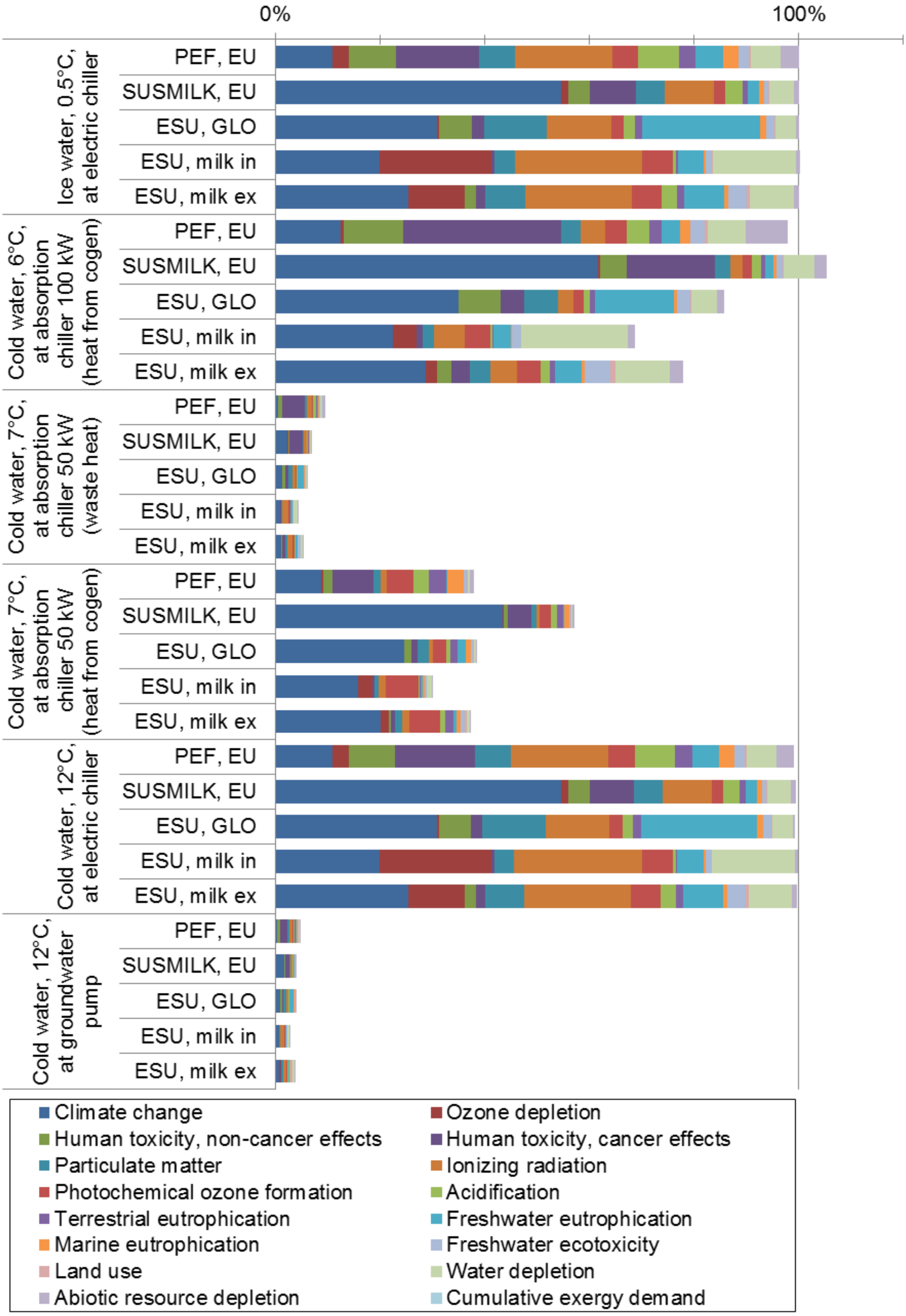

Figure 40 Comparison of cooling options per MJ of cooling provided. Different approaches for normalization and weighting

5.3.5. Improvement scenarios for the whole dairy

The LCA dairy model is compared here with improvement scenarios.

The scenario “exergy optimized“ is based on preliminary results from exergy analysis.[15] The scenario includes a shift to heat and electricity from a natural gas cogeneration unit and a considerable reduction of heat and electricity uses according to the generic dairy model. The reduction in heat demand is achieved with additional heat exchangers. The amount of chromium steel has been roughly assessed and considered with a life time of 15 years. The electricity demand includes the additional electricity as assumed for the LCA dairy model. Allocation between heat and electricity is based on exergy and thus no credit is given for surplus electricity supplied to the grid.

The scenario “environment optimized” is based on recommendations from this LCA study. Here, only the best technologies are considered but the key figures of heat, cooling and electricity demand remain the same.

Within the SUSMILK project, some improvement options were tested. It was not possible to combine these options in one model as both the heat pump and absorption chiller rely on waste heat. Furthermore it is not easy to combine these technologies with solar collectors and pellet boiler in a way that the temperature reached is sufficient.

The main modelling choices are shown in Table 31. The column for the generic model provides the key data as shown in Table 3. There are small deviations in the models calculated in SimaPro e.g. to further upstream uses of certain processes or rounding errors. Due to groundwater cooling, the demand for electricity also decreases in the environmental optimized model. The total natural gas use is about the same as in the LCA dairy model as electricity from the grid is replaced with electricity from the cogeneration unit with natural gas.

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[15] Data provided by A. Jentsch, Richtvert in July 2016.

Table 31 Main assumptions for the modelling of improvement options

			LCA dairy model	Exergy optimized	Environment optimized	Generic model
Electricity	Grid	kWh	57'500			
	Cogen Natural gas	kWh		45'093	46'280	
Generic model		*kWh*	*31'172*	*18'765*	*19'953*	*31'191*
Additonal for LCA model		*kWh*	*26'328*	*26'328*	*26'328*	
Heat	Natural gas boiler	kWh	118'889			119'990
	Cogen Natural gas	kWh		87'225	114'553	
	Large solar	kWh			4'764	
	Heat pump	kWh				
Natural gas	Grid	kWh	152'339	139'358	153'836	149'988
Cold water	Electric	kWh	34'698	3034	-	34'698
	Groundwater	kWh	-	-	34'698	
Ice water	Electric	kWh	9'272	9'272	9'272	9'272
Steel		mg/kWh	8.70	22.54	8.70	-

Figure 41 compares the different improvement scenarios with the base case of the dairy operation without raw milk input. All scenarios lead to an improvement. The exergy optimized scenario and the environment optimized scenario lead to a reduction of about 25% for the total impacts of dairy operation excluding the raw milk input.

It has to be considered that a major share of environmental impacts is not influenced by the improvement options (e.g. the whole delivery of raw milk to the plant or the use of chemicals). The analysis thus shows that several issues have to be taken into account while reducing the environmental impacts of dairy operation. Unfortunately some improvement options concerning e.g. concentration of raw milk or treatment of effluents could not be modelled in the LCA due to lack of data at the time of finalizing the data collection.

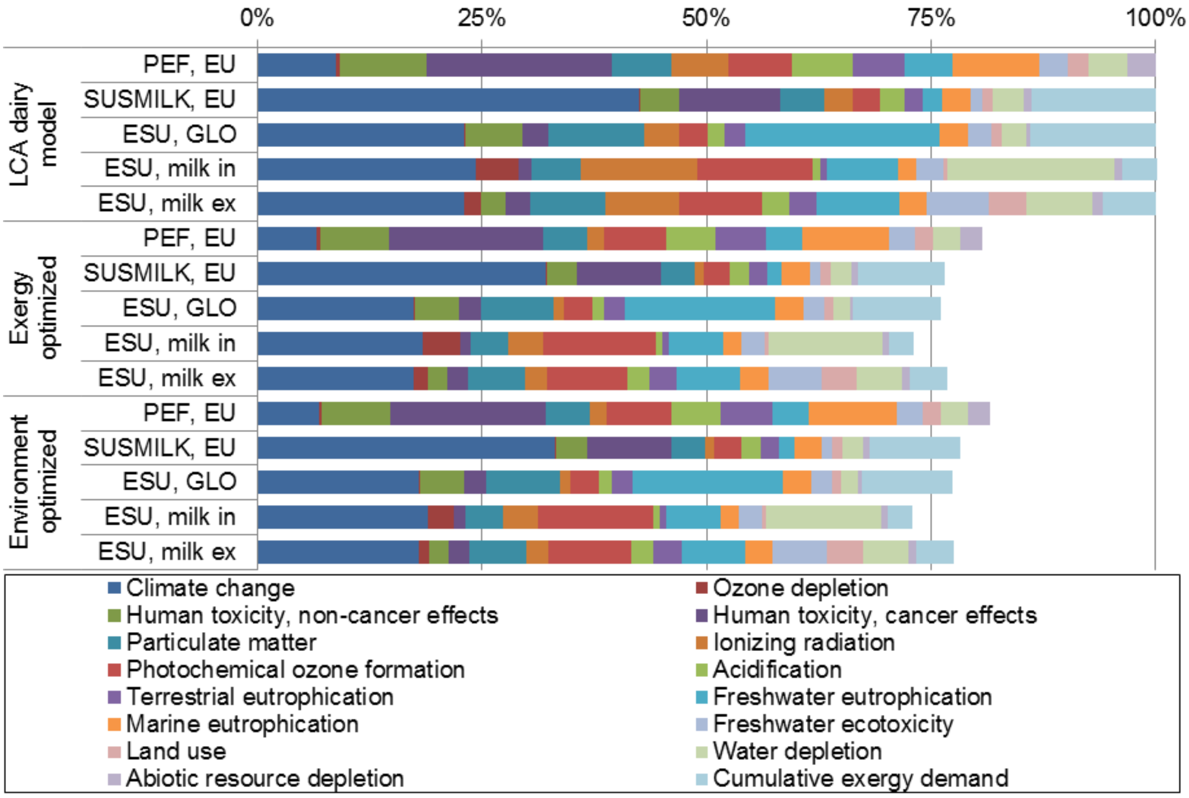


Figure 41 Comparison of improvement scenarios for the daily operation of the dairy

The final scores for the different improvement scenarios are shown in Table 32.

Table 32 Total points according to different normalization and weighting approaches for the LCA dairy model and improvement scenarios

	PEF, EU	SUSMILK, EU	ESU, GLO	ESU, milk in	ESU, milk ex
LCA dairy model	9.42	11.52	16.23	0.19	1.00
Exergy optimized	7.60	8.82	12.35	0.14	0.77
Environment optimized	7.69	9.02	12.56	0.14	0.78

5.4. Conclusions

The evaluation of improvement options based on single category indicators alone does not allow recommendations for several technologies because of results showing pros and cons. Therefore normalization and weighting has been applied in order to facilitate the interpretation of results and to give more guidance for preferable technologies from an environmental point of view.

Several approaches for normalization and weighting have been applied for comparing different improvement options for the supply of heat, cooling and electricity with the present technologies applied in the generic dairy model. In most cases, the approaches come to similar conclusions about the best improvement options. This is even true if there are large differences concerning the importance of different impact categories for the total results. Only the cases where, the improvement options show similar environmental impacts as the generic technology, the normalization and weighting provides diverging results. It can be said that in these cases the uncertainty is too high for providing a clear recommendation.

After evaluating and testing the different approaches, the following recommendations can be made.

The approach developed by ILCD and recommended for PEF (PEF-points) is not recommended by the authors of this study. The uncertainty of some of the underlying category indicators is much too high. Furthermore is it considered to be quite questionable to assign the same weight to all category indicators.

The approaches with an internal normalization are also not recommended. They can give quite biased results for impacts which have a low importance in the considered base case system. An internal normalization only makes sense if there is not a large change in the importance of different category indicators. But, in these cases a direct comparison based on characterized results is normally also sufficient.

The two approaches SUSMILK-points and ESU-points with global weighting are considered to be most meaningful. There are slight differences due to the slightly different approach. But, overall the results can be explained well and they are thus considered as more important for the decision making. For further summaries of the project these two approaches is therefore given first priority.

6. Sensitivity analysis

6.1. Heat supply

6.1.1. Small solar system at Queizuar: Influence of output temperature

The output temperature at the solar collector affects the efficiency of the collector. The impact on climate change for four output temperatures are shown in Figure 42. The increasing heat losses between the collector and the dairy depending on the temperature difference are not taken into account in this comparison. The global warming potential for higher output temperature would increase even more prominently if this was taken into account as well.

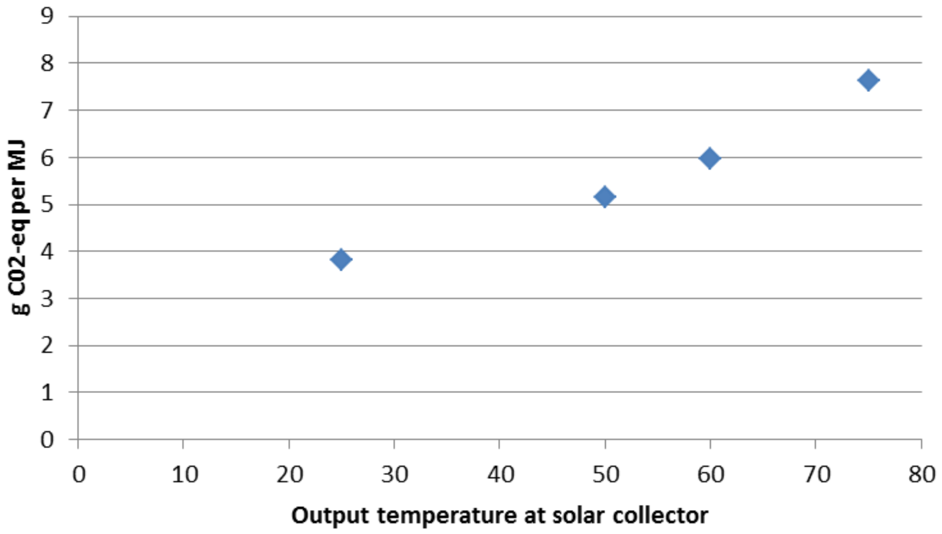


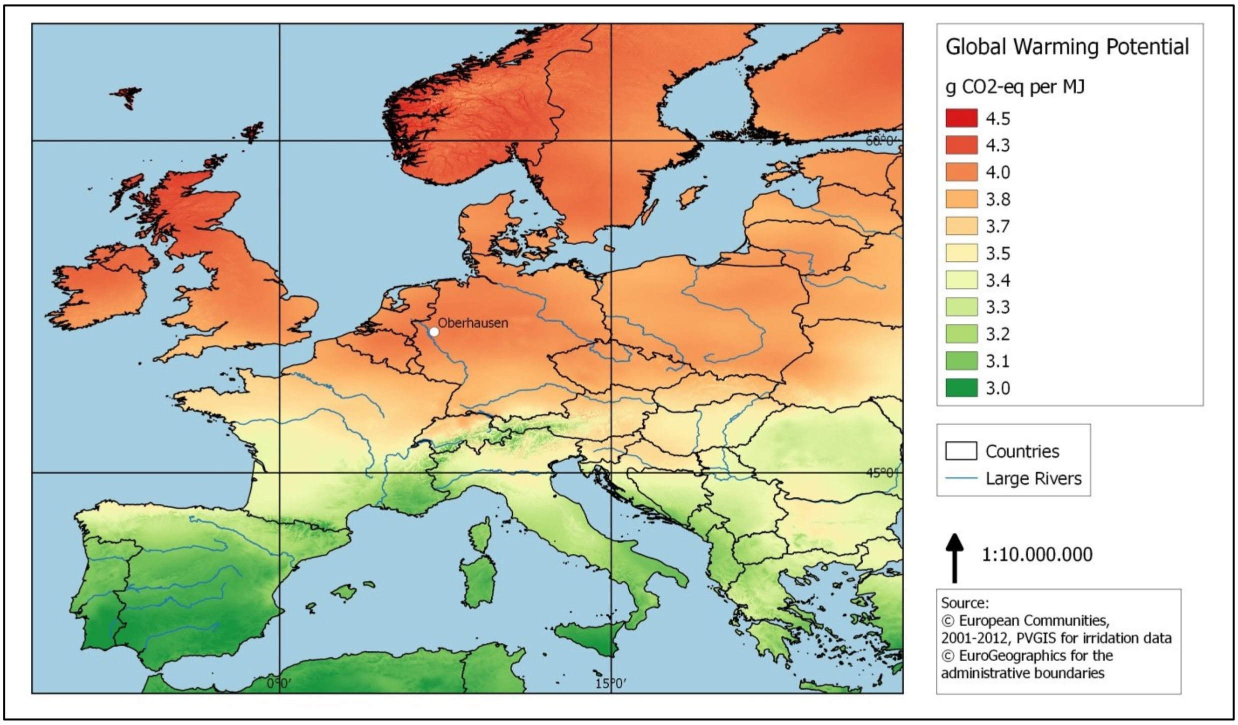
Figure 42 Change of climate change impacts in CO_2-eq per MJ of delivered heat from a small solar collector at Queizuar (Spain) depending on the output temperature at solar collector.

At the same time, high temperatures are more useful than lower temperatures and some processes at the dairy need high temperatures. The integration into an existing heating system at a dairy is easier and leads to less investment costs if high temperatures can be maintained. Furthermore, if the solar collector provides higher temperatures, less additional heating by other means is needed. Therefore the adjustment to medium temperatures is suggested.

The carbon dioxide emissions stem from the production of the solar collectors and the mounting and the electricity for operation (see details in Chapter 4.3.5).

6.1.2. Solar collector: Influence of solar irradiation

The environmental impact of solar collectors strongly depends on irradiation and thus on the location. Therefore a scenario is calculated for the environmental performance at other places than Oberhausen. Based on the modelled solar yields for a 100m^2 solar collector system with SUNeco collectors installed at Oberhausen, Munic and LIsboa and their respective irradiation values, the Global Warming Potential (GWP) per MJ of delivered heat for different irradiation levels is modelled: The electricity demand for operation per MJ of delivered heat is considered constant[16]. The other inputs are modelled depending on the solar yield which is extrapolated from solar irradiation. Figure 43 shows the GWP per delivered heat (g CO_2-eq/MJ) in different regions of Europe as a function of the yearly sum of global irradiation on an optimally-inclined surface. Background irradiation data is ground-station based and is provided by the European Commission Joint Research Centre, Institute for Energy and Transport (JRC 2013)[17].



Source:
© European Communities, 2001-2012, PVGIS for irridation data
© EuroGeographics for the administrative boundaries

Figure 43 Map of Europe showing the impact on climate change in g CO_2-eq per MJ of delivered heat as a function of the irradiation.

The GWP reflects the change in solar irradiation depending on the geographic altitude and increases towards north. In general it can be said that the more south in Europe the solar collectors are installed, the more efficiently the solar system can be used and the lower are the results for the global warming potential.

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[16] Personal communication on 26.6.2016 by Joachim Kalkgruber, SOLARFOCUS.

[17] It refers to the period 1981-1990. The yearly sum of global irradiation in background data varies between 900 and 2000 kWh/m2, with 2 % of minimal and maximal extreme values excluded. The range was then subdivided in eleven categories with equal interval, corresponding to the respective GWP. More details on solar radiation data can be found in JRC 2013.

6.2. Cooling with groundwater

The impact of groundwater cooling depends on the local situation: The height that the groundwater has to be pumped and therefore the electricity needs depends on the groundwater level. The cooling that can be exploited per liter of groundwater depends both on the groundwater temperature as well as on the final temperature that the water reaches after use. For this analysis it is assumed that the groundwater is released into a river and can be warmed to maximal 22°[18]. It is assumed that the whole temperature difference of the water and the resulting cooling provided (calculated with the heat capacity of water) is used in the dairy.

The influence of groundwater level and temperature on climate change is shown in Table 33. The impacts are calculated in the same way as for the cooling comparison, so that the result at Oberhausen is the same as the value for 14m and 12°C groundwater temperature. The groundwater temperature in Europe ranges from 3 to 22° C[19], the groundwater level ranges from 0 to 143m[20].

Even for the highest values reachable within Europe, the impact on climate change per MJ of cooling is still clearly below the impact of both the electrical chiller and the cooling with absorption chiller that use heat from cogeneration (see Chapter 4.5.1). Therefore, groundwater cooling can be recommended considering climate change even with a groundwater level that is deep and a groundwater temperature at 12°C.

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[18] According to the EG Water Framework Directive, the temperature below the discharge point should not be above 21.5°C if the river is a habitat for salmons. Bund für Umwelt und Naturschutz Deutschland (BUND) (2009) Studie: Wärmelast Rhein. Mainz, Germany. P.13. https://www.bund.net/fileadmin/bundnet/publikationen/wasser/20090624_wasser_waermelast_rhein_studie.pdf

[19] Hijmans, R.J.; Cameron, S.E.; Parra, J.L.; Jones, P.G.; Jarvis A. (2005) World Clim. Global Climate Data. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. Assumed same as yearly average of ambient temperature

[20] Fan, Y.; Li, H.; Miguez-Macho, G. (2013) Global patterns of groundwater table depth, Science, 339 (6122): 940-943, doi:10.1126/science.1229881

Table 33 Results in the impact category climate change in g CO2-equivalents per MJ of cooling delivered, depending on groundwater level (GWL) and groundwater temperature

		Temperature (°C)									
		3	4	5	6	7	8	9	10	11	12
Ground water level (m)	0	0.32	0.33	0.35	0.38	0.40	0.43	0.46	0.50	0.55	0.60
	5	0.51	0.54	0.57	0.61	0.65	0.70	0.75	0.81	0.89	0.98
	10	0.71	0.75	0.80	0.85	0.90	0.97	1.04	1.13	1.23	1.35
	15	0.91	0.96	1.02	1.08	1.15	1.23	1.33	1.44	1.57	1.73
	20	1.11	1.17	1.24	1.32	1.40	1.50	1.62	1.75	1.91	2.10
	25	1.31	1.38	1.46	1.55	1.65	1.77	1.91	2.07	2.25	2.48
	30	1.50	1.59	1.68	1.79	1.90	2.04	2.20	2.38	2.60	2.86
	35	1.70	1.80	1.90	2.02	2.15	2.31	2.49	2.69	2.94	3.23
	40	1.90	2.00	2.12	2.25	2.41	2.58	2.78	3.01	3.28	3.61
	45	2.10	2.21	2.34	2.49	2.66	2.85	3.06	3.32	3.62	3.98
	50	2.29	2.42	2.56	2.72	2.91	3.11	3.35	3.63	3.96	4.36
	55	2.49	2.63	2.79	2.96	3.16	3.38	3.64	3.95	4.30	4.74
	60	2.69	2.84	3.01	3.19	3.41	3.65	3.93	4.26	4.65	5.11
	65	2.89	3.05	3.23	3.43	3.66	3.92	4.22	4.57	4.99	5.49
	70	3.09	3.26	3.45	3.66	3.91	4.19	4.51	4.89	5.33	5.86
	75	3.28	3.47	3.67	3.90	4.16	4.46	4.80	5.20	5.67	6.24
	80	3.48	3.67	3.89	4.13	4.41	4.72	5.09	5.51	6.01	6.61
	85	3.68	3.88	4.11	4.37	4.66	4.99	5.38	5.82	6.35	6.99
	90	3.88	4.09	4.33	4.60	4.91	5.26	5.67	6.14	6.70	7.37
	95	4.07	4.30	4.55	4.84	5.16	5.53	5.96	6.45	7.04	7.74
	100	4.27	4.51	4.77	5.07	5.41	5.80	6.24	6.76	7.38	8.12
	105	4.47	4.72	5.00	5.31	5.66	6.07	6.53	7.08	7.72	8.49
	110	4.67	4.93	5.22	5.54	5.91	6.33	6.82	7.39	8.06	8.87

When looking at the situation in Europe (see Figure 44), it is visible that in the southern regions, the groundwater temperature (assumed to be the same as yearly average ambient temperature[21]) is often higher than 12°C. Since our modelling is based on the generic dairy where water at 12°C is modelled as cooling input, groundwater with a higher temperature is not considered in this analysis. Also groundwater with the average temperature below 3°C is not considered, since the water is not in liquid form throughout the year, but partly frozen (often in the mountains). Also excluded are groundwater depths of more than 110m since the expense of drilling a hole that deep is considered rather high compared to the advantages. The figure shows that in most regions (exceptions are most of Spain, Italy and Greece), groundwater use makes sense if the impact on climate change is considered. Other aspects that have to be considered locally are outside the scope of our analysis, like legal requirements and water scarcity in certain regions.

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[21] Stated in National Groundwater Association (2010): http://www.ngwa.org/Fundamentals/studying/Pages/Groundwater-temperature's-measurement-and-significance.aspx

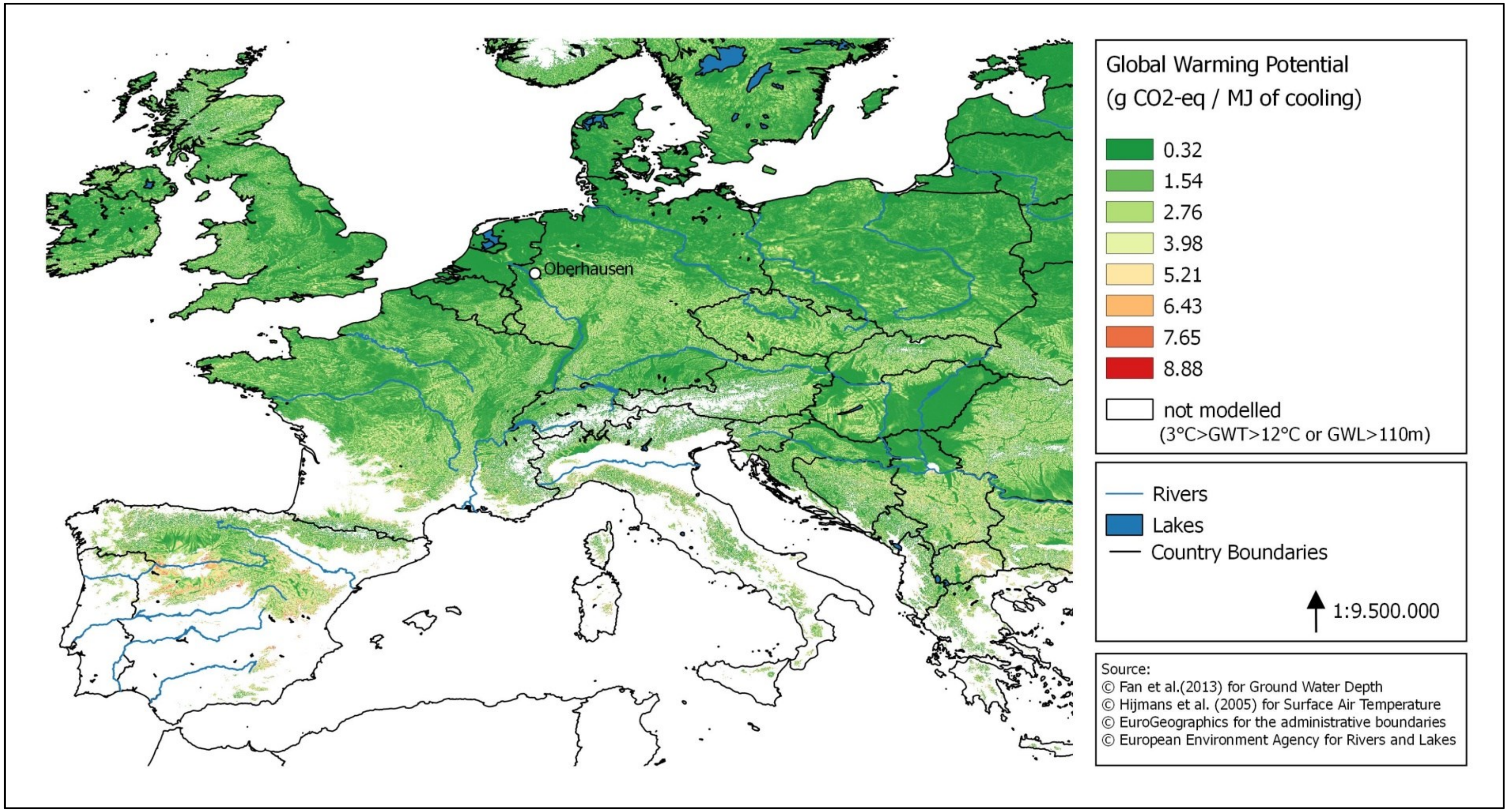

Figure 44 Map of Europe showing availability of groundwater and the impact on climate change in CO2-eq per MJ of cooling depending on the groundwater level and the groundwater temperature.

7. Interpretation and discussion

7.1. Introduction

Within the LCA study of the SUSMILK project a detailed model of dairy operation has been developed and analyzed from an environmental point of view. The model also provides the basis for recommending the best technologies from an environmental point of view for the provision of heat, cooling and electricity. Furthermore it is calculated which reduction of environmental impacts can be expected due to the implementation of such technologies in an optimized dairy.

The detailed results of the analyses in the chapters before are summarized here to final recommendations from an environmental point of view.

7.2. Comparison with literature

The results for single dairy products are quite sensitive to the allocation approach chosen. In this study, the production processes are modelled in detail, so that allocation within the dairy is only needed for the separation step of the raw milk to cream and skim milk and for the additional electricity and water use included in the LCA dairy model. This allocation is conducted according to dry mass content, as suggested by Feitz et al. (2007).

7.2.1. Whole milk

The comparison of the global warming potential of the UHT milk based on the LCA dairy model with literature is shown in Table 34. The whole milk is sensitive to the allocation method. Therefore, it is important to know which allocation method was applied if results from different case studies are compared. The GWP of the UHT milk is comparable to the values found in literature, being in medium range of the results.

Table 34 Literature review for pasteurized whole milk and UHT milk from this study (Landquist et al. 2013)

Reference	Country	kg CO_2-eq /kg milk	System boundaries	Remarks
This study	Europe with Swiss milk	0.92	Allocation according to dry mass content	UHT milk, based on a detailed model, incl. Tetra Brik
Jungbluth et al. 2016a	Switzerland	0.87	whole milk at dairy	Packaging not included, allocation of raw milk by dry mass content, other input economic
Doublet et al. 2013	Romania	1.93 1.45	IDF allocation Alternative allocation (data on milk use, other input economic)	PE bottle incl.
Fantin et al. 2011	Italy	1.3		
Castanheira et al. 2010	Portugal	1.0		
Flysjö et al. 2011	Sweden	0.99 0.73 1.02 1.16	IDF allocation System expansion Economic allocation All to milk	per kg ECM[1] at farm gate
Sheane et al. 2011	Scotland (UK)	1.4	cradle to grave	
Thomassen et al. 2009	Netherlands	1.28		
van der Werf et al. 2009	France	0.98-1.02		per kg FPCM[2]
Sevenster & Jong 2008	EU	0.75-1.65		national inventory reports/UNFCCC data
IDF 2009	Mostly European countries	1.0	not applying the IDF allocation approach	literature review

[1] Energy corrected milk

[2] Fat and Protein Corrected milk

7.2.2. Other dairy products

The comparison of the GWP of yogurt and cream with literature values is shown in Table 35. The GWP of the yogurt in this study is as well in the range of literature values. For cream (40% and 30%), the values obtained are comparable to values from a study on Swiss milk from ESU-services, but much lower compared to the other studies. A possible explanation for this deviation could be that the allocation according to fat or dry mass content assigs a high share of the dairy inputs (i.e. energy) to the cream, even though the actual processes of producing cream might not actually need these high amounts.

Table 35 Literature review for yogurt and other dairy products

Reference	Country	kg CO2-eq/ kg yogurt	Allocation
This study	Europe with Swiss milk	1.51	Based on detailed model, allocation of raw milk separation step according to dry mass content
Büsser & Jungbluth 2009; Jungbluth et al. 2016a	Switzerland	1.18	Packaging not included, allocation of raw milk by dry mass content, other input economic
Doublet et al. 2013	Romania	3.35 1.83	IDF allocation alternative allocation (data on milk use, other input economic)
González-García, 2013	Portugal	1.78	mass allocation
Sheane et al. 2011	UK (Scotland)	1.78	Dry mass allocation
IDF. 2009	Mostly European countries	1.1	Average of different values
		kg CO2-eq/ kg cream	
This study	Europe with Swiss milk	(1) 2.91 (2) 2.70	Based on detailed model, allocation of raw milk separation step according to dry mass content(1) 40% fat, unpacked. (2) 30% fat, packed.
Jungbluth et al. 2016a	Switzerland	2.66	35% fat. Packaging not included, allocation of raw milk by dry mass content, other input economic
Doublet et al. 2013	Romania	5.66 6.87	IDF allocation alternative allocation (data on milk use, other input economic)
Sheane et al. 2011	UK (Scotland)	4.7	Dry mass allocation

7.2.3. Allocation to products

The inputs and outputs of dairy processing are usually only available for the whole plant. There is little information about the assignment of different inputs and outputs to the single dairy products. This assignment is important since it greatly influences the impacts assigned to each dairy product. This chapter aims to present a way of allocation of dairy inputs onto different products, based on the LCA dairy model. These results are compared to the allocation method suggested by the IDF (2010, based on Feitz et al. 2007) and the differences between the two approaches are discussed.

Allocation in this study

The LCA dairy model is built on the generic dairy model of Maga et al. (2016) which is based on a detailed bottom-up modelling of a theoretical generic dairy. It gives the inputs and outputs for more than 40 production sub-processes in the dairy (i.e. separation, pasteurization) and a detailed modelling of CIP (Cleaning-in-place) for each machinery involved. This allows the assignment of inputs and outputs for each sub-process to single dairy products (see Table 36) and thus avoids allocation to a large extent. The raw milk separation step is allocated with milk solids (given in Table 2) as suggested by the IDF (2010) and Feitz et al (2007). The additional inputs included in the LCA dairy model are added to the dataset of the raw milk provision and are therefore allocated in the same manner. For details of the allocation procedure used in this study, please refer to Chapter 3.2.6.

Table 36 Inputs per kg of product given by the LCA dairy model.

	Raw milk	**Water use**	**Electricity**	**Steam use**	**NaOH 50 %**	**HNO3 70 %**	**Waste water**
	kg	kg	MJ	MJ	g	g	l
UHT milk (3.5% fat)	1.0	1.2	0.3	0.4	6.070	1.086	1.261
Stirred yogurt (10% fat)	1.4	1.8	0.5	0.6	1.325	0.096	1.776
Cream (30% fat)	2.9	2.7	0.8	0.8	0.002	0.000	0.003
Concentrated milk (0.2% fat)	2.7	2.8	1.0	2.7	0.012	0.004	0.005
Cream (40% fat)	3.6	2.4	0.8	0.8	1.709	0.124	2.364

Approach of Feitz et al.

Feitz et al. (2007) elaborated an allocation approach based on whole-of-plant data from 17 dairies. First, they collected total input data of dairies that only produce few products, like milk and cream. Later, they subtracted these values from the total input of dairies with a wider product portfolio. Finally, an allocation matrix for dairy products was elaborated that can be applied to whole-of-plant data of dairies with various product portfolios. This approach is part of the IDF recommendation for allocation (IDF 2010, Chapter 6.3.4).

Table 37 first shows the input per kg of market milk[22] according to a model dairy described in the publication of Feitz et al. (Table 37a). Next, the allocation of the sum of inputs for three products[23] (UHT milk, yogurt and cream (40%)) from the LCA dairy model with the method of Feitz et al. is shown (only UHT milk in Table 37b;all three products in Table 38b). The products considered are slightly different; the yogurt of the LCA dairy model has 10% fat, whereas in Feitz et al., yogurts with 0.2 and 3.4% fat are listed. UHT milk has a similar fat content and cream has the same.

The inputs per kg of market milk in the model dairy of Feitz et al. (Table 37a) are similar to the inputs of UHT milk in the LCA dairy model (Table 37b). For raw milk input, this is not a surprise, since the allocation of raw milk to the different products is conducted according to dry mass content (total dry mass content incl. fat) in both approaches. An exception is the chemical input. There, a much higher amount is modelled in the LCA dairy model compared to Feitz et al.

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[22] Only market milk is shown because no other products from the model dairy of Feitz are comparable with the products of the LCA dairy model from this study.

[23] Concentrated milk and cream (30%) are not included in the list of Feitz and are therefore excluded from this comparison.

Table 37 Inputs per kg of market milk from the model of Feitz et al. (a) and per kg of UHT milk for the LCA dairy model (b).

a) Input per kg of market milk according to the model dairy of Feitz et al. (2007)					
	Raw milk kg	*(Waste) water* l/kg	*Electricity* MJ	*Fuel* MJ	*Alkaline* g
Market milk	1	1.5	0.2	0.3	0.8
b) Allocation of the LCA dairy model inputs (based on 3 products) according to Feitz et al. (2007)					
	Raw milk	*Water use*	*Electricity*	*Themal energy*	*Alkaline cleaners*
UHT milk (3.7% fat)	1.1	1.3	0.4	0.5	4.5

Table 38 shows the allocation of the data from the three considered products of the LCA dairy model according to Feitz et al. (Table 38b) and the allocation conducted in the LCA dairy model in this study (Table 38c). It shows that not only the amount of chemicals used for UHT milk is higher in the LCA dairy model compared to the allocation according to Feitz et al., but also the share allocated to UHT milk is higher. In Feitz et al, the same share is suggested for these products. According to Feitz, the resolution in their study was not high enough to identify i.e. different cleaning figures for UHT milk and for fresh milk[24]. By contrast, the values used in the LCA dairy model are specific to the products. They are calculated by defining cleaning programs for different operations based on literature data (assumptions are described in detail in Maga & Font Brucart 2016). The UHT unit and evaporator for the concentrated milk require longer cleaning programs and higher concentrations of chemical products. Plus, recirculation of chemicals and rinse water is not carried out. Since our model shows much higher inputs for UHT milk, there seems to be a substantial difference in chemical use between UHT and normal milk that should be taken into account. Therefore the SUSMILK model is more detailed for allocation for these inputs and could be used to further improve allocation recommendations.

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[24] Feitz, Andrew. Personal communication via e-mail on 14.4.2016.

Table 38 Inputs per kg of product with the allocation proposed by Feitz et al. (2007) for the 3 products yogurt, cream (40%) and UHT milk (b) and inputs given by the LCA dairy model (c).

b) Allocation of the LCA dairy model inputs (based on 3 products) according to Feitz et al. (2007)							
	Raw milk	*Water use*	*Elec-tricity*	*Themal energy*	*Alkaline cleaners*	*Acid cleaners*	*Waste water*
	kg	kg	MJ	MJ	g	g	l
Yogurt (0.2/3.4% fat)	1.2	2.5	1.0	0.9	4.5	0.745	2.535
Cream (40% fat)	3.6	1.3	0.2	0.3	4.5	0.745	1.358
UHT milk (3.7% fat)	1.1	1.3	0.4	0.5	4.5	0.745	1.358
c) Inputs according to the LCA dairy model							
	Raw milk	*Water use*	*Elec-tricity*	*Steam use*	*NaOH 50 %*	*HNO3 70 %*	*Waste water*
Yogurt (10% fat)	1.4	1.8	0.5	0.6	1.325	0.096	1.776
Cream (40% fat)	3.6	2.4	0.8	0.8	1.709	0.124	2.364
UHT milk (3.5% fat)	1.0	1.2	0.3	0.4	6.070	1.086	1.261

Table 39 shows the relative difference of the two allocation results. The comparison of the different allocation procedures shows the smallest difference for raw milk input. Yogurt has more raw milk input in the LCA dairy model because of the higher fat content of the yogurt in the LCA dairy model compared to the yogurt in the publication of Feitz et al. In the other process stages, the results of the two allocation types are very different, especially for cream (40% fat).

The water, steam and electricity use allocated to cream is much higher in our model than in the model of Feitz. In case of electricity, most of the electricity that is used for cream (40% fat) stems from the additional input modelled in the LCA dairy model. This input is added to the raw milk and the allocation of the milk separation step is conducted according to milk solids, therefore a relatively high amount of this additional input is passed on to the cream (40% fat). In the case of water use and thermal energy (in the LCA dairy model: steam for CIP and for heating), most of the input stems from the separation and pasteurization step of raw milk, that is again passed on mainly to the cream. Also, the process of cream (40% fat) production is not set up in an efficient way in the LCA dairy model. This could be an additional explanation why relatively more fuel is needed to produce cream (40% fat) in the LCA dairy model than expected according to the allocation of Feitz et al. Feitz[25] states that they could not differentiate between standard cream and milk and assumed that they need the same amount of inputs. For this aspect, our model is more detailed and could be more accurate.

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[25] Feitz, Andrew. Personal communication via e-mail on 14.4.2016.

Table 39 Relative difference between the data of the LCA dairy model and the allocation of the LCA dairy model data as proposed by Feitz et al (2007) for the 3 products yogurt, cream (40%) and UHT milk. Formula used: (input in LCA dairy model – input Feitz)/input Feitz.

d) Relative change of allocation compared to Feitz et al. (2007)							
	Raw milk	*Water use*	*Elec-tricity*	*Themal energy / Steam use*	*Alkaline cleaners / NaOH 50 %*	*Acid cleaners / HNO3 70 %*	*Waste water*
Yogurt	17%	-29%	-50%	-31%	-70%	-87%	-30%
Cream (40% fat)	3%	76%	356%	207%	-62%	-83%	74%
UHT milk	-7%	-8%	-12%	-16%	35%	46%	-7%

7.2.4. Conclusions

The absolute figures for the environmental impacts of single products found in this study are in the range of other literature studies. This study provides new insights for the allocation of total environmental impacts to single dairy products which is also discussed in a separate article (Keller et al. 2016).

7.3. Recommendations

For the recommendations, the unweighted results (different units according to the characterization method) of all impact categories are considered. These detailed results are accessible in Chapter 4.

This information is complemented with findings from the normalized and weighted single score results (these steps are explained in Chapter 5).

Both types of results are referenced to the conventional technology used in the generic dairy and therefore given in percent. That way, the expected improvement compared to the generic dairy can be assessed.

Restrictions found in the analysis of sensitivities in chapter 6 are considered for the interpretation of results.

The recommendations for single improvement options are described first and overall recommendations are given in the end of this chapter.

7.3.1. Heat supply

Different types of heat provision were compared to heat from a natural gas boiler, including conventional technologies and possible improvement options:

Three conventional technologies to provide heat are considered: natural gas boiler, diesel boiler and light fuel oil boiler.

As improvement options, three cogeneration units (motor and turbine CHP with natural gas and CHP with wood chips), two low-temperature solar systems (installed on open ground and on flat roof), a pellet boiler (with and without particle separator) and a natural gas driven heat pump that uses waste heat are considered.

The installation of a small solar-pellet system at Queizuar that substitute heat from a diesel boiler is also considered as a case study.

In short, the following question is answered in this chapter:

- Which heat supply option should be used from an environmental point of view?

Recommended

From the considered technologies, the gas-engine driven heat pump using waste heat and the cogeneration (motor) with natural gas are clearly the best choice, independent of the evaluation approach. A reduction in almost all[26] fifteen environmental impact categories considered can be expected when they are implemented (average reduction of 50%) and thus all single score results show a reduction.

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[26] The result of heat from a gas-engine driven heat pump is in the same range as the result of heat from a natural gas boiler in the impact category abiotic resource depletion.

Ambiguous results

The results for the large solar system operated with low output temperatures (37° C) have lower impacts in some categories (e.g. climate change) and higher in others. No clear recommendation is possible based on the unweighted results. An installation of a solar system on roof is preferred to an installation on open ground because the impacts for land use are extremely lower for the installation on roof. According to the single score results, the large solar systems are an improvement except for the installation on open ground evaluated with the PEF approach, where the results are in the same range. For some single score approaches, the results of the large solar systems are even lower than the gas-engine driven heat pump and the cogeneration (motor) with natural gas. The recommendation depends highly on weighting and normalization.

For solar systems it is important to consider that they are much more dependent on location than other systems. Solar irradiation, outlet temperature and roof top area available for installation have to be included in an assessment on a case by case basis. Solar systems should be checked as an option in regions with high irradiation, at sites with large roof areas available and when low temperatures can be used for the heat demand. Solar collectors are usually installed with an additional heating system. The assessment thus also depends on how the remaining heat is provided and on the share of heat provided by the collectors. This share is limited by space availability. The case study of the small solar system operated with 60° C output installed in Southern Europe has higher impacts than the theoretical solar systems. The reasons are higher impact of the solar collectors used and the higher output temperature (see sensitivity analysis in Chapter 6.1.1). The results also depend on the losses within the solar collector system that can be higher in a real system compared to the model.

The use of cogeneration (turbine) with natural gas is less recommendable than the cogeneration (motor), since both the heat as well as the electricity of the turbine cogeneration shows higher impacts than the motor. Compared to the natural gas boiler, the impacts in some categories are higher and all others lower. The single score results all show an improvement. Thus, the motor cogeneration is preferable to the turbine cogeneration.

The results for heat from cogeneration with wood are also ambiguous, since impacts are higher in many categories and lower in fewer categories so that no clear recommendation can be given based on the unweighted categories. If the impact categories are weighted and combined to single score results, the cogeneration with wood is lower than the natural gas boiler (reference) for all approaches except the PEF. Thus, the recommendation depends on personal value choices.

The pellet boiler cannot be recommended from an overall environmental perspective since the impacts are considerably to extremely higher in most categories. In the category climate change, the impact is extremely lower, so that only single score approaches that give a high weight to this category show an improvement (e.g. SUSMILK-points). The particle emissions[27] contribute most to the final result of all single score approaches, so that an integration of a particle separator can clearly be recommended. The single score results of the pellet

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[27] The impact assessment method used for this category does not distinguish between different origins of particles, though this may has an effect (see Chapter 5.1.2).

boiler with particle separator show both increase and decrease of environmental impact so that it cannot generally be recommended but depend on the weight given to the different categories and thus on value choices.

Not recommended

The provision of heat with a light fuel oil boiler and a diesel boiler is clearly not recommendable. They only show a reduction in the impact category ozone depletion, but a mostly a considerable to an extreme increase in all other categories including the cumulative exergy demand. All single score results show an increase in environmental impact.

Single impact categories

To have an overall environmental view, the consideration of single environmental impact categories is not sufficient.

Looking only at climate change and ozone depletion, all improvement options can be recommended to replace heat from a natural gas boiler. The two other conventional (light fuel oil boiler, diesel boiler) technologies lead to higher greenhouse gas emissions and cannot be recommended.

The cumulative exergy demand of all options that use wood or solar irradiation as energy source stems mainly from renewable sources, whereas for options that are based on natural gas, diesel or light fuel oil input, the exergy is from non-renewable sources. Therefore, all improvement options based on renewable energy can be recommended if only the source of the cumulative exergy demand is considered.

7.3.2. Electricity supply

Different types of electricity production in cogeneration plants were compared to electricity from European grid: cogeneration with natural gas (motor, turbine) and with wood.

The following question is answered in this chapter:

- Which electricity supply option should be used from an environmental point of view?

Recommended

The cogeneration (motor) with natural gas can be seen as an improvement if all impact categories are considered: In most categories, the impact of the cogeneration is extremely or considerably lower and in some categories only little higher compared to electricity from grid. The only exception is ozone depletion, were the impact is considerably and extremely higher for the cogeneration plant. Since this impact category is not considered reliable, it is not a strong clue to higher impacts.

When the categories are weighted and combined to single score results (Normalization and weighting, see Chapter 5.2), electricity from cogeneration (motor) with natural gas can clearly be recommended.

Ambiguous results

For cogeneration with wood, the result is less clear, but could be seen as an improvement depending on the rating of the different impact categories. In some impact categories, the impacts are considerably to extremely higher, in many lower to extremely lower.

When the categories are weighted and combined to a single score value, the result is unambiguous and electricity from cogeneration with wood can be clearly recommended.

Electricity from cogeneration (turbine) with natural gas has extremely lower to considerably lower impacts in many categories, but also extremely higher impacts in many categories compared to electricity from grid. If the categories are summarized to single score values, the electricity from cogeneration (turbine) with natural gas has higher impacts for most approaches and can therefore not be recommended.

If the results from single score are compared, all electricity considered except for cogeneration (turbine) with natural gas scores better. The main reason for the different outcome between unweighted and weighted results for the cogeneration with wood is that the impact category climate change is given a higher weight in many single score approaches (see Chapter 5.2.5) and therefore strongly influences the final result. Since the burning of wood has a much lower impact on climate change than the burning of natural gas, this alters the evaluation. Therefore, cogeneration with wood can also be recommended, especially if climate change is considered to be an important impact category.

7.3.3. Cooling

Different types of cooling were compared to the reference ice water at electric chiller (0.5° C). The ice water was compared to cooling with cold water (per MJ of cooling provided). The cold water is provided by an electric chiller at 12°C, by an absorption chiller (three types) and by groundwater at 12° C. For the absorption chiller, cold water at 7°C with heat from cogeneration and with waste heat (this study) and cold water at 6°C with heat from cogeneration (generic data) was considered.

The following question is answered in this chapter:

- Which cooling option should be used from an environmental point of view?

Recommended

If the laws allow the use of groundwater for cooling and if no local environmental problem is existent (i.e. water scarcity or temperature of the receiving water body), groundwater cooling can be recommended from an environmental point of view since the impacts in all categories are lower compared to electric cooling. It makes most sense if the temperature of the groundwater and the groundwater level are both low.

If waste heat is available, the use of an absorption chiller that uses this waste heat can also be recommended since the impacts in all categories are lower compared to electric cooling.

If a cogeneration unit is installed at the dairy to provide heat, the absorption chiller (6 C, this study) driven by this heat can also be recommended, though the reduction is much lower compared to groundwater cooling or cooling by a waste-heat driven absorption chiller. The single score results (see Chapter 5.2) also show a clear improvement compared to electrical cooling, though the improvement is less prominent than for groundwater cooling or the waste-heat driven absorption chiller. It can be recommended if the other two options are not possible.

Ambiguous results

The cooling from a cogeneration unit (natural gas) as modelled in ecoinvent leads to less clear results: The impacts in most categories are lower and in some categories higher. The results hint to a reduction of environmental impact, but no clear recommendation can be given based on the unweighted results. The single score shows a reduction in most of the approaches. The reduction potential is lower compared to the other improvement options. The recommendation therefore depends on the value choices.

Dependencies

Since some cooling options depend on waste heat availability, the best option for cooling depends on the decision taken for the heat supply.

7.3.4. General insights for dairies

The highest improvement potential from a cradle to gate perspective lies in the raw milk production since this process stage contributes 50% up to almost 100% of total impact in the 16 environmental categories considered. Therefore all other process stages are of minor importance if raw milk production is included in the assessment. Thus the production systems used for the raw milk have a decisive role for the overall environmental impact of dairy products and should be given priority in environmental improvement strategies.

For the dairy operation excluding raw milk production, the amount of packaging used and an efficient transport of the raw milk to the processing plant are important as well as adequate waste water treatment. For these process stages, high shares of environmental impact from cradle to gate excluding raw milk input are reached in different categories. All percentages stated in this paragraph refer to this impact, i.e. excluding raw milk production.

As second priority, the electricity uses in the dairy can be reduced. They have a high share in the categories ionizing radiation (70%) and water depletion (30%) and also contribute to other impact categories (between 4% and almost 40%).

The use of steam (sum of CIP and production) contributes most in the impact categories climate change and ozone depletion (30%) and cumulative exergy demand (a quarter), but only contributes little in the other categories. If these categories are considered important, a focus on this process stage is recommended. An intelligent process design that reuses heat within the dairy and an efficient evaporation can be used to decrease heat demand.

Chemicals contribute less than 5% in all categories except human toxicity, non-cancer effects, where they contribute less than 10%. Therefore the reduction of chemical use can only contribute little to the reduction of the environmental impact of operation and should not be in the focus of environmental impact reductions.

7.3.5. General insights for producers of equipment

The reduction of the amount of material used, the extension of the lifetime of the system and the energetic efficiency reduces the environmental impact of all devices in general.

Also, the use of recycling aluminum and the facilitation of recycling at the end of life can help reducing the impact of production of primary aluminum.

For the pellet boiler, the emission control is crucial to reduce the impacts in the category particulate matter when changing fuel from natural gas to pellets.

The emissions from the gas engine, especially the nitrogen oxide emissions, have a crucial impact in many environmental impact categories. It should be aimed at a reduction of these emissions.

To improve the environmental performance of the absorption chiller, an increased efficiency of the cooling process as well as the reduction of the steel input can contribute most.

Outlook

Electricity production on the dairy site would be an interesting option for larger dairies. If electricity is bought from the grid, the electricity mix of Europe is used. Investments in certificates for renewable energy only make sense if the invested money is used to build renewable electricity power plants. Else, neither the electricity mix nor the environmental impacts of electricity use change.

7.3.6. The generic dairy model

This LCA benefitted very much from the analytical details of the generic dairy model, which was developed in the SUSMILK project (Maga et al. 2014; Maga & Font Brucart 2016). The heat and water demands estimated for the generic dairy are within or close to the ranges reported in the literature for European dairies. But, the amount of electricity is only about half of what can be found in literature.

A shortcoming of the model is the limited number of products covered. Important dairy products like butter, cheese and milk powder are not covered in the model. As there is no cheese in the model, also whey as an intermediate product is not investigated. Whey is a major point of discussion if it comes to the effluent treatment and the possibilities for using the whey (Kopf-Bolanz et al. 2015a, b).

Nowadays, dairies also produce a range of variants of typical products e.g. milk with different fat contents, different packages or for special dietary requirements. Such developments and details are also not covered by the present model.

The limited product portfolio in the model made it difficult to investigate some developments in the SUSMILK project e.g. regarding the pre-concentration processes for raw milk and effluents. Also advanced waste water treatment processes could not be compared to the generic dairy model because the model lacks details on the present treatment of effluents.

7.3.7. Overall recommendation

The major impact of dairy products is due to the production of raw milk (about 80%). For the analysis done in this project this was not the focus of investigation. But, dairies also have an influence on these impacts, e.g. by reducing the amount of raw milk and other losses of dairy products.

The best way to decrease the environmental impact of heat, cooling and electricity demand is the reduction of the needed amount, as an example with a clever process design and the integration of heat exchangers.

The next best way is the integration of improvement options that substitute conventional energy delivery. The options developed in this project can lead to some reductions of environmental impacts of dairy operation. The improvement scenarios from the environmental and exergy point of view can lead to a reduction of about 25% for the total impacts of dairy operation excluding the raw milk input. If only technologies developed within the SUSMILK project are considered, the possible reduction of environmental impacts is a bit lower and amounts to only 10% to 20%.

It has to be considered that a major share of these environmental impacts is not influenced by the considered improvement options (e.g. the whole delivery of raw milk to the plant, the use of chemicals or the treatment of effluents). The analysis thus shows that several issues have to be taken into account while reducing the environmental impacts of dairy operation. Unfortunately, some improvement options developed in the SUSMILK project e.g. concerning concentration of raw milk or treatment of effluents could not be modelled in the LCA due to lack of data at the time of finalizing the data collection.

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