NTNU
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Environmental Impacts of Renewable Energy

An Overview of Life Cycle Results

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Master in Industrial Ecology
Submission date: July 2010
Supervisor: Edgar Hertwich, EPT

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Problem Description

Background and objective

The use of fossil energy is the main contributor to many environmental pressures and the fuels will ultimately be depleted. A transition to renewable energy sources hence appears necessary. Renewable energy technologies, however, have substantial land requirements and require more investment in infrastructure to harvest the energy. Environmental impacts hence are of different nature and to a degree earlier in the life-cycle, that is, in the construction of the power plants rather than their operation.

One of the rationales for the development of life-cycle assessment is to study trade-offs such as those between the construction of renewable power plants and the operation of fossil ones. While many LCAs have been conducted for renewable power plants, little work has been done to compare the LCA results of different technologies. EcoInvent is one of the best data sources for life-cycle inventory data. While not offering a comprehensive review of all LCAs in an area, the advantage is that the inventories contained are structured according to a common format and common data collection principles, including for system boundaries. EcoInvent hence offers an opportunity to analyse the environmental impacts of renewable power production.

The objective of this study is to compare important technologies of renewable power production as presented in EcoInvent, including wind energy, bioenergy, and solar energy in terms of their overall environmental attributes, and to provide an understanding to what degree these attributes depend on material production and land use or other scarce factors. A comparison with NGCC and pulverized coal power plant is also desirable to identify the trade-offs.

This is the second topic assigned to the student as the first topic could not be answered due to a lack of cooperation on part of the industry organizations that were meant to provide data for analysis.

The following questions should be considered in the project work:

- What are the land requirements per EJ of electricity production (or GtCO2 avoided per year)?
- How large are material requirements for producing the necessary power plants?
- How large are emissions of pollutants (evaluated according to LCA impact categories)?
- What fraction of the emissions-based impacts (GHG, PM) is due to materials production?
- What other life-cycle steps contribute significantly to the total environmental impact?

Assignment given: 08. February 2010

Supervisor: Edgar Hertwich, EPT

Summary

Selected non-renewable and renewable energy processes from the ecoinvent 2.2 life cycle inventory database were analysed using basic contribution analysis, geometric series expansion, and structural path analysis. The hierarchical perspective of the ReCiPe impact assessment method was applied. The sources studied included biomass, wind, solar photovoltaic, hydropower, natural gas combined cycle and hard coal. Several technologies within each energy source were studied for comparison purposes. The processes were compared based on material consumption, land use and emissions for the production of 1 EJ (278 TWh).

Results indicate that all of the renewable energy sources studied had a significantly lower impact than the non-renewable sources chosen. With the exception of bioenergies and pumped reservoir hydropower, technologies for the same energy source showed similar behaviour in the analyses performed.

The findings from this study confirm previous work stating the environmental and human health superiority of renewable energy technologies over fossil fuel energy.

Sammendrag

Utvalgte ikke fornybare og fornybare energi prosesser fra livssyklus databasen ecoinvent 2.2 har blitt analysert ved å bruke grunnleggende kontribusjonsanalyse, geometrisk serie ekspansjon og strukturell stianalyse. Det hierarkiske perspektivet til ReCiPe sin påvirkningsanalyse har blitt brukt. Energikildene som har blit undersøkt inkluderer biomasse, vind, fotovoltaisk solteknologi, vannenergi, kombinert syklus naturgass og kull. Flere teknologier innenfor hver enkelt energikilde har blitt undersøkt for å få et utstrakt sammenligningsgrunnlag. Prosessene var sammenlignet basert på materialfrobruk, landarealbruk og utslipp fra produksjonen av 1 EJ (278 TWh).

Resultatene viser at alle de fornybare energikildene undersøkt hadde betydelig lavere påvirkning enn de ikke fornybare energikilden. Med unntakene bioenergi og vannpumpekraftverk, så viste teknologiene for den samme energikilden lignende oppførsel i analysen.

Funnene i dette studiet bekrefter tidligere arbeid som erklærer at fornybare energi er bedre enn fossilt brennstoff både innenfor miljø og menneskets helse.

Preface

The road to this thesis certainly was a rocky one! The experience of having two thesis topics in a semester is one I will hopefully not have to experience again! Thankfully, it was not a journey I had to undertake on my own. There are many people for whom I must thank for their work and support.

First and foremost, thanks goes to my supervisor, Edgar Hertwich, who always had advice to give throughout this process, and who had the will to say “this won’t work, let’s start again.”

Credit must also be attributed to Troy Hawkins, Glen Peters and Yasushi Kondo, whose work was essential to the success of this thesis. Troy’s extraction of the ecoinvent 2.2 database and ReCiPe characterization matrices allowed this work to contain the most recent data possible. His support with troubleshooting the data was also extraordinarily helpful. The structural path analysis code used in the study was written by Glen Peters, and modified by Yasushi Kondo.

I am also indebted to Guillaume Majeau-Bettez for his work and resources that were used in this thesis. In addition, his never-ending willingness to discuss and brainstorm and his unwavering moral support were crucial to the completion of this work. I also wish to express gratitude for Ryan Bright’s assistance, advice and most of all, patience with my spontaneous drop-in question sessions.

Finally, the support, welcome distractions and companionship of my colleagues in MSc IndEcol ’08 were invaluable. In particular, thanks go to Kristin Fjellheim, whose constant presence at nighttime café work sessions kept my sanity intact.

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NTNU

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MASTER THESIS

Stud.techn. Christine Hung
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Environmental Impacts of Renewable Energy: A Overview of Life-Cycle Results

Miljøkonsekvenser av fornybar energi: Oversikt over livssyklus resultater

1.1

Background and objective

The use of fossil energy is the main contributor to many environmental pressures and the fuels will ultimately be depleted. A transition to renewable energy sources hence appears necessary. Renewable energy technologies, however, have substantial land requirements and require more investment in infrastructure to harvest the energy. Environmental impacts hence are of different nature and to a degree earlier in the life-cycle, that is, in the construction of the power plants rather than their operation.

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Within 14 days of receiving the written text on the diploma thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

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Two – 2 – copies of the thesis shall be submitted to the Department. Upon request, additional copies shall be submitted directly to research advisors/companies. A CD-ROM (Word format or corresponding) containing the thesis, and including the short summary, must also be submitted to the Department of Energy and Process Engineering

Department of Energy and Process Engineering,

Olav Bolland	Edgar Hertwich
Department Manager	Academic Supervisor

Table of Contents

Table of Figures

List of Tables

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1. Introduction

As environmental issues, in particular climate change, become increasingly important, energy use and supply come under intense scrutiny. The sheer magnitude of global energy use and its rapid growth have severe environmental implications.

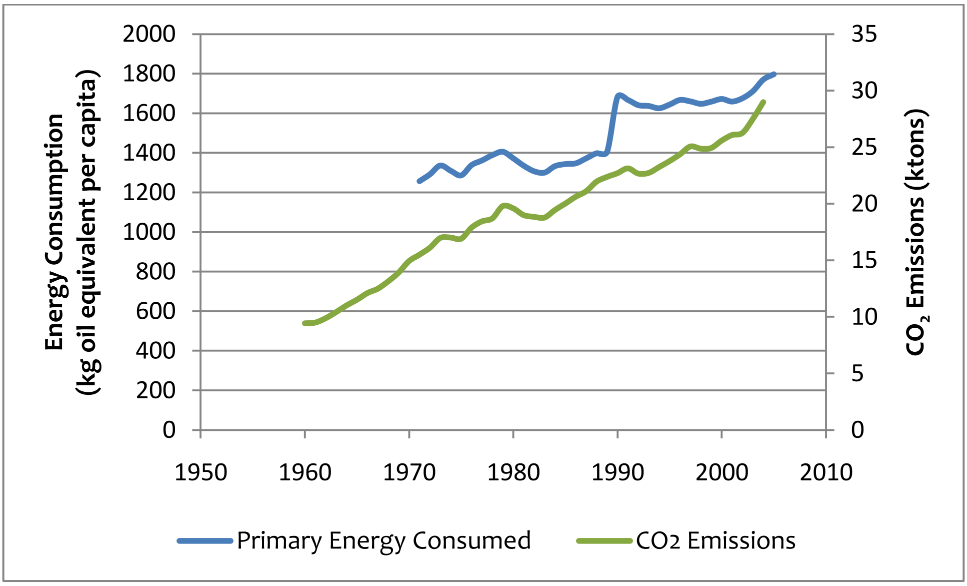

Figure 1.1: World primary energy consumption and CO_2 emissions. (The World Bank)

The global human population continues to grow, and countries are continuing to develop, causing steep increases in the demand for energy. At the current rate of increasing energy use, energy demand is expected to increase 65% from 2004 levels by 2030 (Sims, Schock et al. 2007). However, the majority of energy currently used globally is derived from non-renewable sources (Ristinen and Krushaar 2006; Sims, Schock et al. 2007), (Figure 1.2).

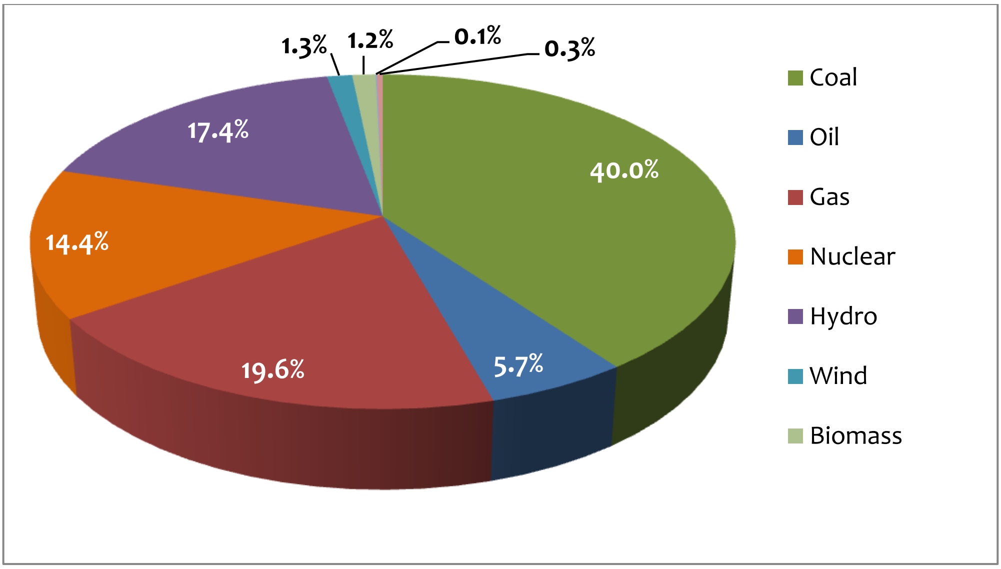

Figure 1.2: Shares of energy sources used in electricity production, 2007. (Lenzen 2010)

Although energy is principally used in two forms, heat and electricity, this study focused on electricity. Although the goal of this work is to determine the environmental impact of renewable energy in general, examining electricity production exclusively provides a consistent baseline on which energy sources can be compared. In addition, as one of the most versatile energy carriers available today, electricity is steadily increasing its share of the energy market and plays an important role in development indices (Ferguson, Wilkinson et al. 2000; Lenzen 2010).

Non-renewable energy sources such as fossil fuels and nuclear ores have a rate of replenishment on the order of millions of years, and are currently being used a rate significantly greater than that of replenishment. Consequently, there is a finite reserve of non-renewable energy sources, and once these reserves have been emptied, alternative sources of energy must be used.

Renewable energy sources are those which are replenished at a rate greater than they are consumed. Renewable energy sources include solar energy, some forms of biomass, tidal and hydropower and wind.

Due to increasing concerns about climate change and energy security, nations are making an effort to increase energy efficiency and switch over to renewable sources of energy. In the European Union (EU), 20% of the final energy consumption EU is for electricity, 9.6% of which was supplied by renewable energy technology in 2006. This number is just short of the goal of 21% renewable energy by 2010 set by the Directive 2001/7/EC (European Union 2010).

Renewable energy sources are generally considered to be "climate-friendly," and allow countries with no fossil fuel reserves to gain energy security and independence (Asif and Muneer 2007). Critics of renewable energy, however, argue that the relatively low energy density of these energy supplies, or rather, of the low efficiency of the technologies used to convert the energy, render a world using exclusively or even primarily renewable energy impracticable (Ausubel 2007). In some cases they argue that renewable energies have poorer performance than the fossil fuel and nuclear energy sources used today (Ausubel 2007).

While the need to improve the environmental performance of energy systems is clear, the question of whether renewable energy systems are truly superior to non-renewable energy systems must be addressed. In general, renewable energy technologies are lauded for their performance in producing minimal quantities of greenhouse gases. However, other environmental impacts such as effects on acid rain production, ozone depletion, ecosystem destruction, release of carcinogens, etc, are often overlooked in studies and popular media coverage.

Since energy is being used in such enormous quantities and growing at such a rapid pace, it is crucial that policy makers truly understand the full implications of adopting a new energy technology.

The goal of this study is thus *to compare the overall environmental impact of some important non-renewable and renewable electricity production processes using life cycle assessment.*

The environmental assessment method used in this study is life cycle assessment and employing processes from the ecoinvent life cycle inventory database. Processes were selected to reflect European technology, specifically Swiss technology, whenever possible. This is done in order to maintain consistency, due to the fact that most of the processes in the ecoinvent database are based on Swiss data. The comparison of the non-renewable and renewable energy sources is limited to the impacts included in the ReCiPe impact assessment method selected (see Chapter 0, Methodology). As a result, certain impacts may not be included in this assessment. This is typically due to limited availability of quantitative data linking processes or emissions to these omitted impacts (Goedkoop, Heijungs et al. 2009).

This work begins with a brief overview of the energy sources considered. The energy sources selected for this study are those currently playing the most significant role in the renewable energy market. Basic contribution analysis, geometric series expansion and structural path analysis were performed on the selected processes. Results from the different renewable energy sources and non-renewable sources are compared. Different technologies harnessing the same renewable energy source are also compared to establish the potential range of impacts for a given energy source.

2. Background

2.1 Non-renewable Energy Technologies

Most non-renewable energy sources are fossil fuels (International Energy Agency 2009). The non-renewable energy sources used as a baseline to which renewable technologies are compared in this study are hard coal and natural gas.

2.1.1 Coal

Coal is currently the dominant fuel source for electricity production (Letcher 2008). Several forms of coal exist, which vary in carbon content. The energy density of coal increases with the carbon content. In addition, higher carbon content results in a cleaner-burning fuel (Ristinen and Krushaar 2006). Anthracite, or hard coal, is the cleanest burning and most energy-intensive form of coal. The fuel is combusted to produce steam, which turns a turbine to generate electricity.

The main environmental concerns associated with conventional coal combustion include the emission of CO_2, SO_2, NO_x and mercury (Letcher 2008). Due to the prevalence of coal combustion and abundant supply of coal in the world, it is important that improvements be made to the coal combustion process. The most recent and significant advances include improvement to combustion efficiencies by using different combustion techniques, implementation of enhanced flue gas cleaning equipment, coal transformation technologies, integrated gasification combined cycle and carbon capture and storage (CCS) technologies (Chen and Xu 2010).

2.1.2 Natural Gas

Natural gas has gained in momentum as an energy source in recent years. As a fuel, natural gas combustion emits less pollution than other fossil fuels as it is generally low in impurities, and is versatile in its application.

Natural gas combustion fuels the production of steam, which powers electricity-generating turbines. In a combined-cycle natural gas power plant, different thermodynamic cycles may be combined to improve overall plant efficiency (Kehlhofer, Rukes et al. 2009). The first cycle operates at a higher-temperature while the second harnesses the energy contained in the resulting waste heat. Due to the higher efficiency of these facilities, the environmental impact per unit of electricity or natural gas consumed decreases. Most new gas-fired power plants constructed today in North America and Europe are combined-cycle.

2.2 Renewable Energy Technologies

2.2.1 Solar

Solar energy, as the name implies, exploits the energy from solar radiation to produce usable energy. There is significant potential in this source of energy: the total solar radiation intercepted by Earth is on the order of 8000 times greater than the human primary energy demand (Letcher 2008). Unfortunately, the ability of humans to effectively collect and transform this energy remains severely limited.

Currently, two methods of harnessing solar energy exist: concentrated solar power (CSP) and solar photovoltaics (PV). The former involves focusing, or concentrating, solar energy to heat a working liquid to produce steam which in turn powers a turbine. The latter, photovoltaics, uses cell arrays to capture solar energy and convert it into direct current electricity (Letcher 2008). Only photovoltaic energy is considered in this work.

Various PV technologies currently exist and the area is still developing rapidly. High-purity silicon is usually the material of choice in solar PV cells. The general concept behind solar PV is that the incoming solar radiation is absorbed by a solar cell. The energy in the photons promotes electrons in the solar cell, creating an electric potential. Cell arrays may be grouped in large collection to form a sun farm, or installed on rooftops and building facades as a decentralized source of energy (Letcher 2008).

2.2.2 Wind

Wind energy is harnessed using wind turbines on land or at sea (offshore). Kinetic energy from the wind is converted to mechanical energy in a gearbox. The majority of modern wind turbines consist of three-bladed rotors. The rotors are connected to a low-speed shaft. In order to increase the speed of the shaft, the gearbox increases to shaft speed to match the rotational speed of a induction generator (Letcher 2008).

While wind farms require a large area to produce a commercially viable quantity of electricity (Letcher 2008), very little of the land – approximately 3% – is actually occupied by the turbines. As a result, most of the land the wind farm “officially” occupies may still be used for grazing or tillage, as an example.

The advantage of offshore wind farms is that the effect of visual impact is reduced, and the open ocean provides a very good wind resource. However, since these sites are isolated and at sea, they may be difficult and costly to construct and maintain (Letcher 2008). As fossil fuel prices rise, however, offshore wind projects may become more economically viable.

2.2.3 Bioenergy

Biomass is generally looked favourably upon as a renewable energy source. One reason this source is frequently promoted is that much of the CO_2 emitted from its combustion, is offset by the CO_2 absorbed by the plant during its life cycle to produce biomass (Kruger 2006). However, studies have shown that the carbon sequestration capability of a mature tree, for example, is much greater than that of the resulting cleared area. In addition, the relatively instantaneous release of carbon stored in wood biomass has a significantly larger impact on global warming than the gradual decomposition process that would occur in a forest (Johnson 2009). The chemical composition of biomass is also low in sulphur, resulting in lowered SO_2 emissions over those of fossil fuels (Kruger 2006).

Biomass can be converted to electricity through several different media; it may be combusted as-is, or converted to liquid or gaseous fuels. Some of these media are described below.

Traditional Biomass Energy

The traditional use of biomass considered is the combustion of biomass, used throughout the times for space heating and cooking. However, in developing countries where biomass is still used in open-air stoves, pits and fireplaces, there is concern with emitted air pollutants. Of particular concern are particulate matter, volatile organic compounds (VOCs), dioxins, etc. resulting from incomplete combustion (Lavric, Konnov et al. 2004). These pollutants are of concern both environmentally and health-wise for the occupants of the building (Lavric, Konnov et al. 2004) especially as there are rarely emissions controls in place. Industrial-scale biomass combustion facilities

Biowaste

The dominant fraction of municipal solid waste consists of biodegradable matter, such as food waste, paper and yard waste (Ristinen and Krushaar 2006). These wastes are simultaneously dried and combusted in a specially designed furnace. The heat is used to produce steam, and in turn, run a turbine, producing electricity (Ristinen and Krushaar 2006). This process is usually implemented principally as a waste management rather than as an electricity generation measure; the municipalities involved benefit more from reducing solid waste going to landfill than from gaining an additional source of electricity (Ristinen and Krushaar 2006).

Bioethanol

Ethanol is one form of liquid fuel that can be derived from biomass. The biomass, in the form of carbohydrates, municipal wastes or livestock manures, is hydrolyzed and then anaerobically fermented to produce ethanol (Letcher 2008). The ethanol fuel must subsequently be distilled and dehydrated to remove water (Letcher 2008).

Bioethanol is commonly mixed with conventional fossil fuels (usually gasoline) to optimize the fuel performance and the environmental impact (Ristinen and Krushaar 2006). The addition of bioethanol increases the oxygen content of the fuel, thereby encouraging more complete combustion and reducing CO emissions.

Biogas

Biomass in the form of manure, industrial food waste, agricultural residues and sewage can also be anaerobically digested to produce biogas. Biogas consists mainly of methane (CH_4), carbon dioxide (CO_2) and water. Trace contaminants, such as ammonia and sulphides may also be present (Letcher 2008). Digestion conditions and the chemical composition of the biomass being digested affect the ratio of methane to carbon dioxide.

2.2.4 Hydroelectric

Hydroelectric power converts potential energy in water, in the form of head, to kinetic energy, which in turn is converted to electrical energy. Two general types of hydroelectric technologies exist: run-of-river and reservoir, or storage.

Reservoir

In the reservoir scheme, a dam is constructed, creating a large water reservoir. Water is released in a controlled manner, dropping in altitude and driving a turbine.

The benefit of a reservoir scheme is clear: the timing of electricity production is greatly controlled, allowing for more consistent electricity supply. The excess water can be stored from melt periods or periods of high rainfall, and reserved for times of low rainfall. In addition, the dam also controls the water, allowing complete shut-off of the turbines for times of low electricity demand. However, the environmental impact of reservoir hydroelectric projects is significantly greater than run-of-river, as land, which is often forested, is flooded, displacing both humans and wildlife.

Pumped

Pumped storage schemes are motivated primarily by economic influence rather than environmental benefits. In this design, once the water has passed through the turbine, it is pumped back up to the reservoir. This renders the facility less vulnerable to seasonal variations in rainfall levels, allowing for more consistent and constant production of electricity for peak periods of electricity demand.

Run-of-river

Run-of-river hydroelectric projects are characterized by the continuous discharge of water; this technology relies on the existing displacement of water to power the turbine. As a result, water is not stored for on-demand electricity production, and the head is constant with the seasons (Letcher 2008).

3. Methodology

3.1 Tools Used

A Matlab script was written to perform the calculations in this study. While other alternatives exist, such as the SimaPro LCA software, or a graphical user interface (GUI) developed by Majeau-Bettez (2010), the development of this script proved to be more appropriate for the study. The custom script optimizes the output format of results for the analyses performed and allows for many processes to be calculated simultaneously, as opposed to using most GUIs, where each process would have to be analyzed individually. It should be noted that since results are written to a Microsoft Excel file, that the script runs quite slowly, especially when multiple processes are to be analyzed at once.

All of the analyzed processes were obtained from the ecoinvent database, version 2.2. The inter-industry matrix, ***A***, stressor matrix ***S***, and characterization matrices, ***C***, were obtained from the Ecoinvent Centre and processed by Troy Hawkins of the Industrial Ecology programme at NTNU. Prior to calculations, the ***A*** matrix had to be manipulated. Because of the manner in which the ecoinvent database interprets flows, the diagonal entries in the ***A*** matrix, that is, the contributions of all process to themselves, were had been entered as -1. In order to obtain 0s on the diagonal, as with traditional ***A*** matrices, a vector with 1s in all elements was diagonalized and added to the ***A*** matrix.

The assessment method used, ReCiPe version 1.3, has both midpoint and endpoint indicators available. The single-score endpoint indicator and the hierarchical, or middle-ground, perspective were used in the majority of the calculations performed. A focus was also placed on global warming potential (GWP), particulate matter formation (PM) acidification potential, ozone depletion and land occupation and transformation (Dincer and Rosen 1999).

3.2 The ReCiPe Method

ReCiPe is a life cycle impact method released in 2008 (Goedkoop, Heijungs et al. 2009). The goal of ReCiPe is to harmonize midpoint and endpoint impact categories in a single framework. This method builds on the previously existing Centrum Milieukunde Leiden (CML 2002) and Eco-indicator 99 methods, the latter of which uses the endpoint approach, and the former, midpoint (Goedkoop, Heijungs et al. 2009).

Midpoint and Endpoint Indicators

The advantage of using the ReCiPe framework for this work thus becomes clear: the results can be presented using either or both midpoint or endpoint indicators. These indicators have been developed using a system consistent in the methods and level of detail included in the models used to develop the indicators (Goedkoop, Heijungs et al. 2009).

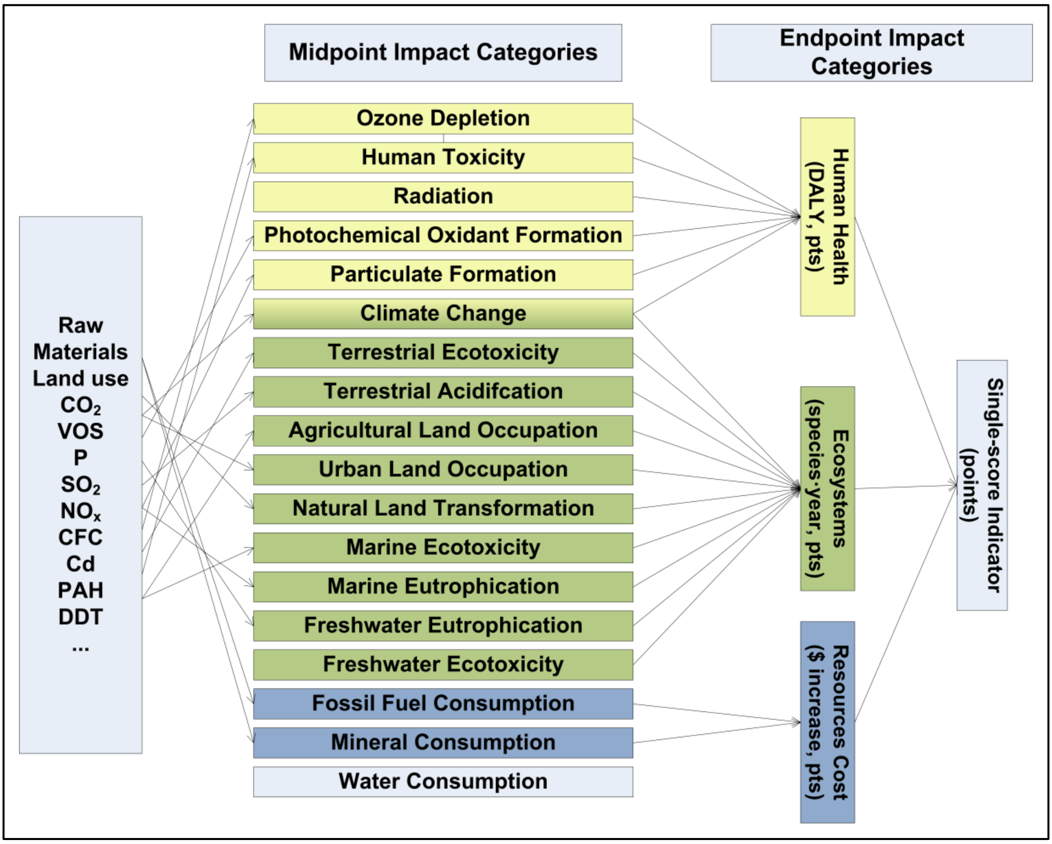

Figure 3.1: Relationship between life-cycle inventory results, midpoint indicators and endpoint indicators.
Modified from (Goedkoop, Heijungs et al. 2009)

There are eighteen midpoint impact categories and three endpoint impact categories in the ReCiPe method. Characterization factors are used to convert emissions to the units of the midpoint impact categories, and from midpoint to endpoint. Note that the midpoint impact category of 'climate change' contributes to both the 'damage to human health' and 'damage to ecosystems' endpoint categories. The relationship between the midpoint and endpoint impact categories is shown in Figure 3.1.

There are both advantages and disadvantages to using midpoints and endpoints. Midpoints are generally fairly accurate, but the units, usually in terms of a reference compound, such as CO_2 for climate change, can render it difficult for the analyst or a policy maker to understand the overall impact. In contrast, endpoints are much easier to conceptualize. Endpoints are expressed in terms of tangible effects using a point system, dollar amounts, number of species affected, or number of human life years lost (DALY), to which it is easier to relate. However, the method of translating the midpoint impacts to endpoint units incorporates much uncertainty. This uncertainty stems from poor understanding of the mechanisms through which pollutants affect ecosystems and human life and the dependence these mechanisms may have on geographical factors. Thus, the tradeoff between result accuracy and result interpretation becomes quite evident.

Perspectives

Three scenarios, or perspectives, have been developed in the ReCiPe method. These scenarios reflect the various sources of uncertainty in the models used to link midpoint and endpoint categories. The perspectives are:

- **Individualist (I)**: a short-term perspective, using only undisputed impacts. Assumes an optimistic scenario with regards to technological developments and human adaptation.
- **Hierarchist (H)**: "middle-ground" perspective. Uses most common approach for time-frame and included impacts.
- **Egalitarian (E)**: the most conservative perspective. Uses the longest time perspective and includes impacts that include some uncertainty.

The Hierarchist perspective was used throughout this study.

3.3 Processes Analyzed

The final demand used in the study is 1 EJ, or 278 GWh of electricity produced. Since commercial power generation in a single facility can reach more than twenty gigawatts (GW) (Wang and Chen 2009), such a large demand provides a more accurate representation of the impact of the analyzed processes on a large scale.

The ecoinvent processes were carefully selected to obtain a fair representation of the technologies investigated. These technologies may be found in Table 3.1, which classifies the technologies by energy source and provides the formal ecoinvent 2.2 process name as well as the short form name subsequently used in this report. An effort was made to ensure that the processes selected represented the most common incarnation of the technology. In addition, to maintain consistency, the process representing Switzerland was used whenever possible.

For most renewable energy sources, there exist several technologies that can convert the energy to electricity. To explore the breadth of impact of the various possible implementations of renewable electricity, several types of technologies for a given energy were analyzed. This provides an indication with respect to the range of impacts that can be expected for a given renewable energy source.

Table 3.1: List of ecoinvent 2.2 processes studied.

Category	Process Name (ecoinvent 2.2)	Short Name
Bioenergy	electricity, biowaste, at waste incineration plant, allocation price, CH	Biowaste
	electricity, at cogen 6400kWth, wood, allocation energy, CH	Wood
	electricity, at cogen 6400kWth, wood, emission control, allocation energy	Wood, EC
	electricity, at cogen with biogas engine, allocation exergy, CH	Biogas
	electricity, bagasse, sweet sorghum, at distillery, CN	Bioethanol, sorghum
	electricity, wood, at distillery, CH	Bioethanol, wood
Hydropower	electricity, hydropower, at pumped storage power plant, CH	Hydro, pumped
	electricity, hydropower, at reservoir power plant, CH	Hydro, reservoir

	electricity, hydropower, at run-of-river power plant, CH	Hydro, run-of-river
Wind	electricity, at wind power plant, CH	Wind, average
	electricity, at wind power plant 2MW, offshore, OCE	Wind, offshore
	electricity, at wind power plant 600kW, CH	Wind, 600 kWh
	electricity, at wind power plant 800kW, CH	Wind, 800 kWh
Solar	electricity, PV, at 3kWp flat roof installation, multi-Si, CH	PV, multi-Si
Photovoltaic	electricity, PV, at 3kWp flat roof installation, single-Si, CH	PV, single-Si
Non-	electricity, hard coal, at power plant, UCTE	Coal
renewable (baseline)	electricity, natural gas, at combined cycle plant, best technology, RER	NGCC

3.4 Life Cycle Assessment

Life cycle assessment (LCA) is an analytical method in which the inputs, outputs and environmental impacts of a product system are compiled and evaluated. As the name implies, all aspects of the product system life cycle is considered: manufacture, distribution, operation (or use) and disposal.

The method of performing an LCA is dictated by the general ISO 14040 standard. The four phases of an LCA are goal and scope definition; inventory analysis; impact assessment; and interpretation (Heijungs and Suh 2002). Of particular interest in this study are impact assessment and interpretation. The four phases are briefly described below.

The goal and scope definition phase establishes the context of the study. The functional unit and system boundary of the study are chosen. In some cases, the functional unit may be obvious, but in other cases, it may be more challenging to select an appropriate unit (Matheys, Van Autenboer et al. 2007). It is important to select an appropriate functional unit as the results may be biased one way or another depending on the unit chosen (Matheys, Van Autenboer et al. 2007). The selection of system boundaries may also influence the results (Udo de Haes and Heijungs

2007). However, this shortcoming in LCA was somewhat avoided in this study by exclusively using processes from the ecoinvent database, which sets a standard for how the inventory is built, including the system boundaries.

The inventory analysis is the most labour-intensive stage in performing an LCA. The processes related to the product system must be determined. Data is collected regarding these processes, which may include extraction of raw materials, disposal processes and transportation. The material and energy inputs and outputs of and the emissions produced by these processes must be tabulated. Some processes with multiple outputs may require allocation, or distribution of impact amongst the multiple outputs. This data collection process is continued down the process chain as far as is practical.

In the impact assessment stage, the inventory of emissions released are converted to an equivalent quantity of a reference compound, and aggregated into impact categories. As an example, the emissions of carbon dioxide (CO_2), methane (CH_4), and ozone (O_3), among others, are converted to kilogram equivalents of CO_2 (kg CO_2-eq) and reported as global warming, or climate change, potential. Results from impact assessment may be further processed in order to present a single-score indicator of environmental impact. The impact assessment may present midpoint or endpoint indicators as the analyst decides. The benefits and weaknesses of each are discussed in §3.2.

The interpretation stage is important as it is in this phase that the true meaning and context of the results are explored. The uncertainty of the data retrieved is assessed, and results may be subjected to a sensitivity analysis or compared to similar products and studies. A final judgment on the meaning of the results is made.

3.4.1 Computational Foundations of Basic Contribution analysis

As its name implies, the basic contribution analysis consists of the most basic level of calculations in life cycle assessment. These calculations allow for the determination of physical process outputs, $\boldsymbol{x}$, for a given final demand, $\boldsymbol{y}$. The vector of total process output can then be used to determine the emissions and impacts resulting from $\boldsymbol{y}$.

Table 3.2: List of variables used in life cycle assessment

Symbol	Description	Dimensions[1]
x	Output vector	*pro x 1*
y	Final demand vector	*pro x 1*
I	Identity matrix	*pro x pro*
a	Inter-industry requirements matrix	*pro x pro*
L	Leontief Inverse $(I-A)^{-1}$	*pro x pro*
S	Stressor matrix	*str x pro*
e	Total emissions vector	*str x 1*
E	Total emissions, by process	*str x pro*
C	Characterization matrix	*imp x pro*
d	Total impacts vector	*imp x 1*
D	Total impacts, by process	*imp x pro*
Z	Material requirements matrix	*pro x pro*
z	Total material requirements	*pro x 1*
Zagg	Material requirements matrix, aggregated	*agg x agg*
Dagg	Total impacts, by aggregated categories	*imp x agg*
$\mathbf{T}_{EI2.2\text{->}agg}$	Aggregation matrix, ecoinvent to aggregated categories	*pro x agg*
$\mathbf{T}_{EI2.2\text{->}IO}$	Aggregation matrix, ecoinvent to input-output categories	*pro x io*
$\mathbf{T}_{IO\text{->}agg}$	Aggregation matrix, input-output to aggregated categories	*io x agg*

Physical process outputs, $\boldsymbol{x}$, are determined using the inter-industry requirements matrix, $\boldsymbol{A}$ (Equation(1.1)). The inter-industry requirements matrix acts as a recipe book: each column contains the products and quantities required for producing a unit of the process in question. As an example, the value of element $\boldsymbol{a}_{21}$ represents the amount of process 2 required to produce a unit from process 1. The sum of all elements $\boldsymbol{a}_{i1}$ would provide all that is required to produce a single unit from process 1. Thus, the total output is the sum of the intermediate demand and the final demand:

$$x = Ax + y \tag{1.1}$$

[1] Dimensions specified are: *pro*: number of processes in ecoinvent; *str*: number of stressors; *imp*: number of impact categories, *agg*: number of aggregation categories; *io*: number of input-output sectors

Rearranging for ***x*** gives

$$x = (I - A)^{-1}y \tag{1.2}$$

which can be rewritten in terms of the Leontief inverse, ***L***:

$$x = Ly \tag{1.3}$$

The emissions can be determined by multiplying the total output by the stressor matrix, ***S***, which itemizes the emissions released per unit production of a process:

$$e = Sx \tag{1.4}$$

The environmental impacts resulting from a process can then be calculated using a characterization matrix, ***C***, specific to the method selected, in this case, the ReCiPe method. The analyst can calculate midpoint or endpoint indicators by using the appropriate characterization matrices.

$$d = Ce \tag{1.5}$$

While calculating ***e*** and ***d*** may be quite useful, further information can be gathered if we slightly modify Equations (1.4) and(1.5). If we diagonalise the vectors being multiplied in these equations, we obtain the emission and impact contribution from each stressor or process:

$$E = S\hat{x} = S\widehat{Ly} = CS\widehat{(I - A)^{-1}y} \tag{1.6}$$

and

$$D = CE = CS\hat{x} \tag{1.7}$$

Finally, the material flow matrix, ***Z***, may be determined by using the following property from physical input-output tables (PIOT) (Nakamura, Nakajima et al. 2007).

$$A = Z\hat{x}^{-1} \tag{1.8}$$

which gives

$$Z = A\hat{x} \tag{1.9}$$

However, $\boldsymbol{Z}$ provides the material flows between processes, and in this work, only the total material flows is of interest. Thus, the total material flow determined by multiplying by the undiagonalised total output vector:

$$z = Ax \tag{1.10}$$

The material aggregation matrix, $\boldsymbol{T_{agg}}$, is then applied to determine the total quantity of materials used according to the aggregation categories selected for the study:

$$Z_{agg} = T_{agg}Ax \tag{1.11}$$

3.5 Development of Aggregation Matrices

In order to simplify the assessment of general sector contributions to impact, the processes were aggregated into sixteen main categories. This was done by first using a correlation table linking the ecoinvent 2.2 processes (*EI2.2*) to the International Standard Industrial Classification of all Economic activities, revision 4 (ISIC rev. 4), reducing the number of sectors to 154. a second table was used to aggregate the ISIC rev. 4 classifications to the sixteen classifications (*agg*) used in this work. This second table was assembled manually. The final aggregation matrix was then obtained by multiplying the two matrices to obtain an aggregation matrix, $\boldsymbol{T}$, which has the dimensions *pro* x *agg*.

$$\mathrm{T}_{\mathrm{EI2.2 \to agg}} = \mathrm{T}_{\mathrm{EI2.2 \to ISIC}}\mathrm{T}_{\mathrm{ISIC \to agg}} \tag{1.12}$$

Process-specific matrices can then be 'broken down' into the sixteen categories by being multiplied by $\boldsymbol{T}$:

$$D_{agg} = T_{EI2.2 \to Agg}D_{pro} = T_{EI2.2 \to Agg}(CS\hat{x}) \tag{1.13}$$

In the case of the material flow matrix, $\boldsymbol{Z}$, aggregation presents a more complex problem. Although several processes may all be members of the same sector, the functional units of these processes are not all the same. For example, the ISIC rev 4. category "Manufacture of articles of concrete, cement and plaster," contains the two processes "concrete block, at plant" and "concrete, normal, at plant." The former has the functional unit of kilograms, while the latter has a functional unit of m^3. Thus, if the aggregation matrix is applied to the material flow matrix, $\boldsymbol{Z}$, each aggregated sector would contain mixed units. This would render the results meaningless as a single number would contain contributions from kg of one material, but m^3 of another. To avoid this issue, the aggregation matrix $\boldsymbol{T}_{EI2.2\rightarrow agg}$ (Equation(1.12)) was modified to only include those processes with a functional unit of kilograms. The coefficient of processes with other functional units was set to 0. This ensures that only units of mass are summed together. The resulting aggregation matrix, $\boldsymbol{T}_{agg}$, was used to in Equation (1.7) to determine the impact of materials in the processes studied.

3.6 Geometric Series Expansion

a given final demand will trigger a chain of processes. For example, in the production of electricity using wind energy, the construction of a wind turbine is required. In turn, the construction of the wind turbine requires steel and concrete for the turbine body and the construction of the generator. These processes require the processing of raw materials, which require mining of ores, etc. etc. This chain of processes may continue on to infinity as far as it is practical to consider. (Figure 3.2)

Geometric series expansion is used to determine the relative impact of each 'tier' of the process chain. This allows the analyst to determine where the majority of the impact occurs in the process chain, whether the impacts occur within the first tiers (near the 'foreground'), evenly throughout the process chain, or in the later tiers ('background').

$$\sum_{t=0}^{\infty} r^t = 1 + r + r^2 + \cdots + r^n = (1-r)^{-1} \quad \text{for } r < 1 \qquad (1.14)$$

$$\sum_{t=0}^{\infty} A^t = 1 + A + A^2 + \cdots + A^n = (I - A)^{-1} = L \text{ for } \rho(A) < 1 \qquad (1.15)$$

$$\sum_{t=0}^{\infty} A^t y = y + Ay + A^2 y + \cdots + A^n y = Ly = x \text{ for } \rho(A) < 1 \qquad (1.16)$$

as shown in Equation(1.16), the total output $\boldsymbol{x}$ may be expressed as a geometric expansion. From the definitions of the final demand, $\boldsymbol{y}$, and inter-industry matrix, it is evident that when both sides are multiplied by $\boldsymbol{y}$, each term in the series is the output from each 'tier' of the system. The output of a given tier is equal to the product of the inter-industry demand matrix and the demand, or input of that tier (which is equal to the output of the tier 'below' (Figure 3.2)

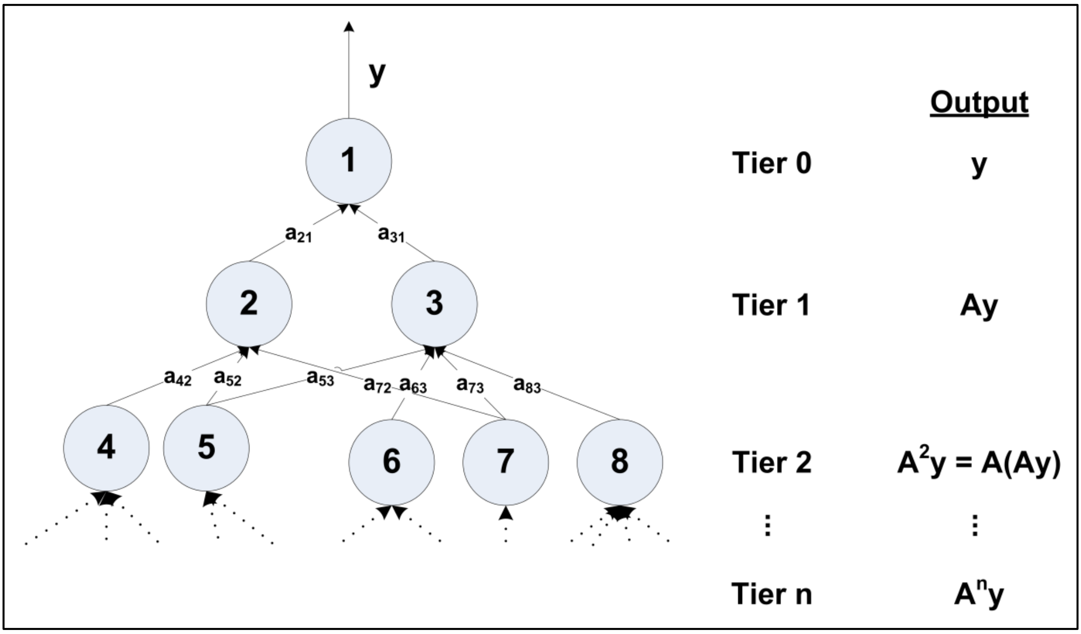

Figure 3.2: Demonstration of tiers and geometric series expansion.

The impact contribution of each tier can be determined by multiplying Equation (1.16) with the stressor and characterization matrices:

$$\sum_{t=0}^{\infty} CSA^t y = CSy + CSAy + CSA^2 y + \cdots + CSA^n y = CSLy = d \qquad (1.17)$$

The series expansion was performed on the total single-score endpoint indicator to obtain a general perception of where the majority of the process impacts occur.

For a given tier t, the total output may be generalized as:

$$x_t = Ax_{t-1} = A^t y \qquad (1.18)$$

The impact at each tier is thus:

$$d_t = CSx_t \qquad (1.19)$$

When the accumulated impact is plotted as a function of the tier number, the analyst obtains a visualization of where the dominant processes lie by observing whether foreground or background processes play a larger role in the process impact.

3.7 Structural Path Analysis

The structural path analysis (SPA) was performed using the code developed by Glen Peters (2005) and Edgar Hertwich (Peters and Hertwich 2006), and modified by Yasushi Kondo (Kondo 2010). The code was further modified for this study to allow the export of the results directly to Excel. The code explores paths with a length up to the maximum number of tiers set by the user and has a contribution to the total emissions or impact greater than or equal to the user-defined tolerance. The code sorts the paths found in order of decreasing contributions, and outputs the number of paths satisfying the conditions set by the user. Additional output includes the sorted list of paths, the nodes of each path, the path length and the path contribution to overall emissions or impact.

The tolerance was set to 0.005%, and the maximum number of tiers was set to fifteen (15). Both the geometric series expansion and SPA were performed on the single-score total endpoint indicator.

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4. Results

4.1 Emissions

The results of the impact assessment for the energy systems studied are presented in Table 4.1. a brief glance at Table 4.1 shows that the coal combustion plant has by far the highest emissions for nearly all categories. The exceptions are ozone depletion, ionizing radiation, and terrestrial ecotoxicity, which shall be discussed below. The impact categories of particular interest here, namely climate change, terrestrial acidification, particulate matter formation and ozone depletion, are presented in Figure 4.1 to Figure 4.3. The other impact categories shall be briefly discussed afterwards.

CO_2-Equivalent Emissions (Climate Change)

Emissions of CO_2 range from the order of 0.98 Mt $CO_2 \cdot EJ^{-1}$ electricity produced (Hydro, run-of-river) to 300 Mt $CO_2 \cdot EJ^{-1}$ electricity produced (Coal). This clearly shows a significant advantage with all of the renewable energy systems over both non-renewable energy sources studied. This agrees with results found in previous studies (Jacobson 2009). Of the renewable energies studied, biogas, followed by pumped reservoir hydropower and biowaste combustion have the highest emissions.

For biogas and biowaste, this may be due to allocation. Since the feedstock for these processes is usually considered a waste product from another process such as food production, these feedstocks would likely not be granted any credits for carbon uptake of biomass during its growth phase. Biogas and biowaste would then be associated with the full emissions resulting from their combustion. Another potential contributor to the high climate change impact of biogas may be fugitive emissions. Since the composition of biogas is principally CH_4 and CO_2, any leaks in a biogas facility would increase the climate change impact of the plant.

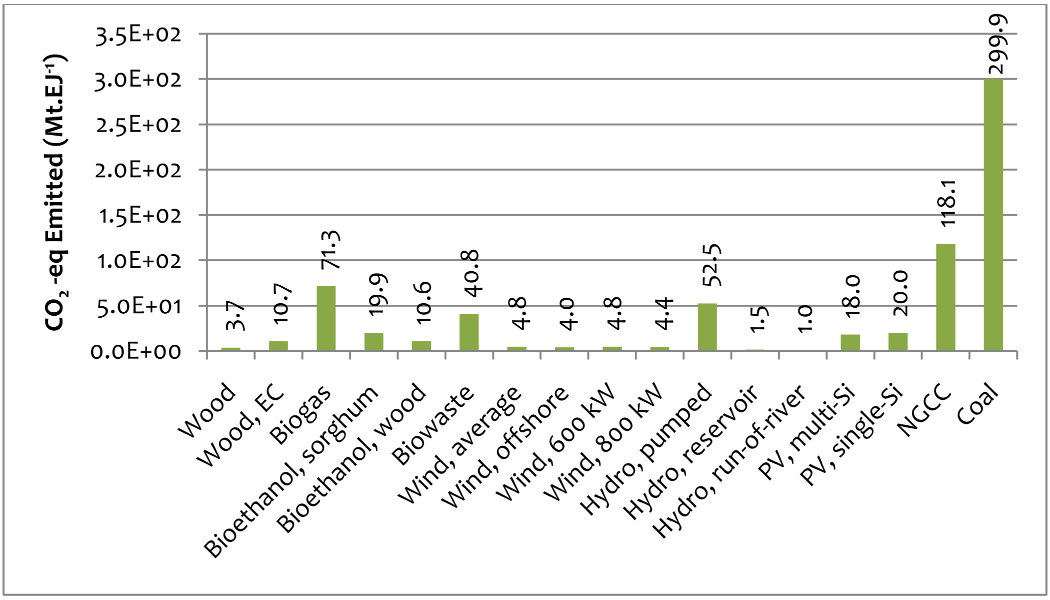

Figure 4.1: Emissions of greenhouse gases for renewable and non-renewable energy technologies.

The pumped reservoir hydro plant undoubtedly has a relatively high global warming potential due to the combustion of fossil fuels used to drive the pumps returning the water to the upper reservoir. In comparison, the conventional reservoir hydropower, which is a nearly identical technology, with the exception of this pumping process, has negligible CO_2 emissions.

Solar PV also makes a fairly significant impact. This is due to the energy-intensive silicon purification process (Jungbluth, Stucki et al. 2009), wherein fossil fuels are combusted.

PM10 Emissions (Particulate Matter Formation)

a similar comparison can be made in the particulate matter formation impact category. The range calculated here varied from 4.6 to 383 kt PM10·EJ^{-1} electricity produced. as shown in Figure 4.2, coal again emits the most, although there is less difference between the PM10 emissions of coal and the next highest emissions from a renewable source than with CO_2 emissions.

The bioenergies emit the most PM10 of the renewable energies. In the case of the technologies involving the direct combustion of biomass (Wood; Wood, EC;

Biowaste), this is expected as these fuels are known for producing high levels of particulate matter (Lavric, Konnov et al. 2004). In the case of sorghum bagasse, however, the fuel is bioethanol rather than the bagasse itself. In this case, the explanation is likely that the particulates come from the handling of the bagasse fibres (National Pollutant Inventory 2001).

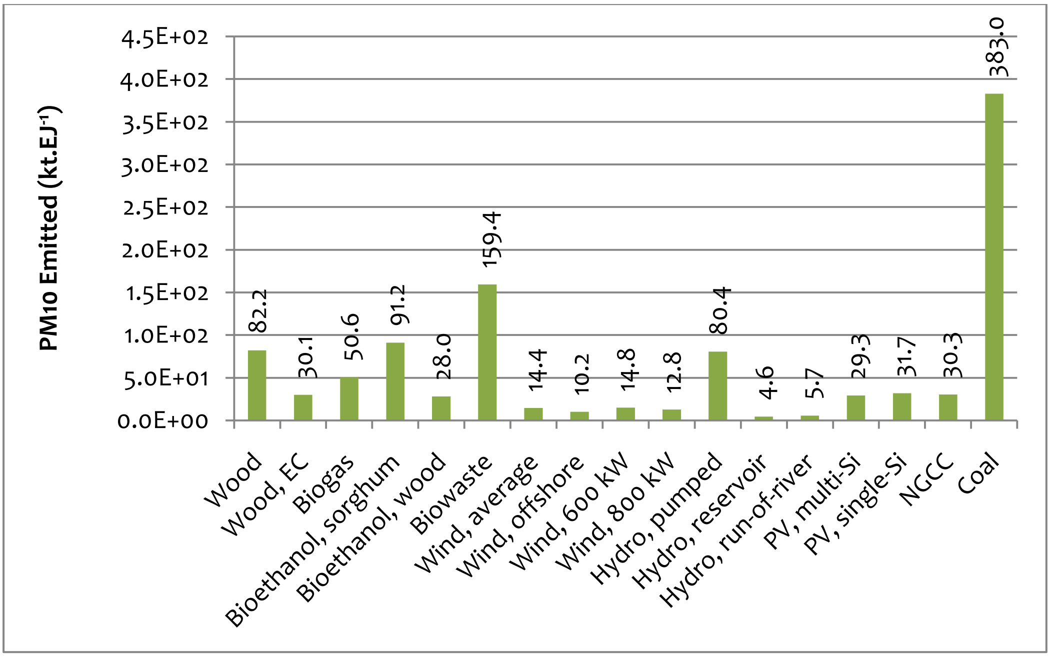

Figure 4.2: Emissions of particulate matter less than 10 µm for renewable and non-renewable energies.

The solar photovoltaic technologies emit approximately the same amount of PM10 as the natural gas power plant. This may be due to manufacturing process, where fossil fuels are combusted, and perhaps also due to the wafer sawing process, which would create fine silicon dust particles.

SO_2-Equivalent Emissions (acidification)

Finally, with the acidification potential, represented by the terrestrial acidification impact category, coal unsurprisingly proves to have the highest emissions of the processes studied (Figure 4.3). Indeed, the figure echoes the trends found those for climate change and particulate matter formation. This is not unexpected, as it is commonly known that coal releases large quantities of acidifying compounds (Larssen, Lydersen et al. 2006) responsible for acid rain.

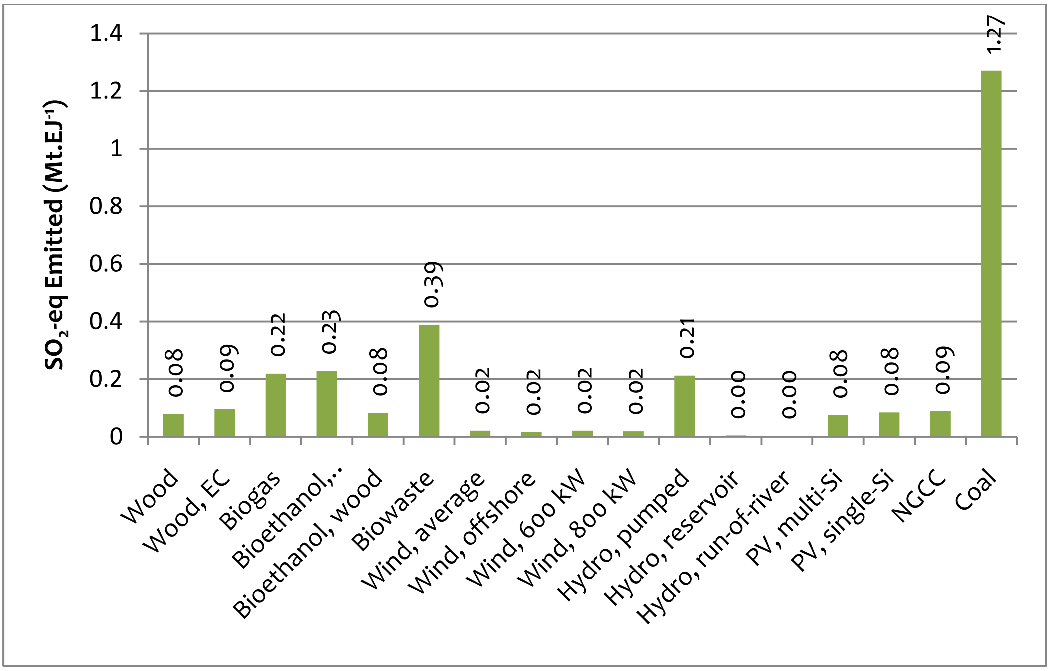

Figure 4.3: Emissions of SO_2-eq (acidification potential) from renewable and non-renewable energies.

Again, the bioenergies show high results for the acidification factor. For sorghum bioethanol, this might be due to the acid used in the hydrolysis pre-treatments step for the ethanol fermentation process (Kadam 2000). Similarly for the biogas, the feedstock undergoes a microbial-driven anaerobic digestion, beginning with a hydrolysis step (Lastella, Testa et al. 2002) and producing acetic acid.

The pumped reservoir hydropower plant also shows high emissions once again. These emissions are also likely attributable to the combustion of fossil fuels used to power the pumping process. The photovoltaics also have a notable impact, likely due to fossil fuel use in the manufacturing process (Jungbluth, Bauer et al. 2005).

CFC-11-Equivalent Emissions (Ozone Depletion)

In Figure 4.4, notable differences from the previous three figures examined immediately become clear. Natural gas has the highest impact in ozone depletion. all of the emissions of significance, however, have some element of combustion involved either as the process itself or in its manufacturing process. The ozone depletion impact of these processes is likely due to incomplete combustion forming NOx emissions.

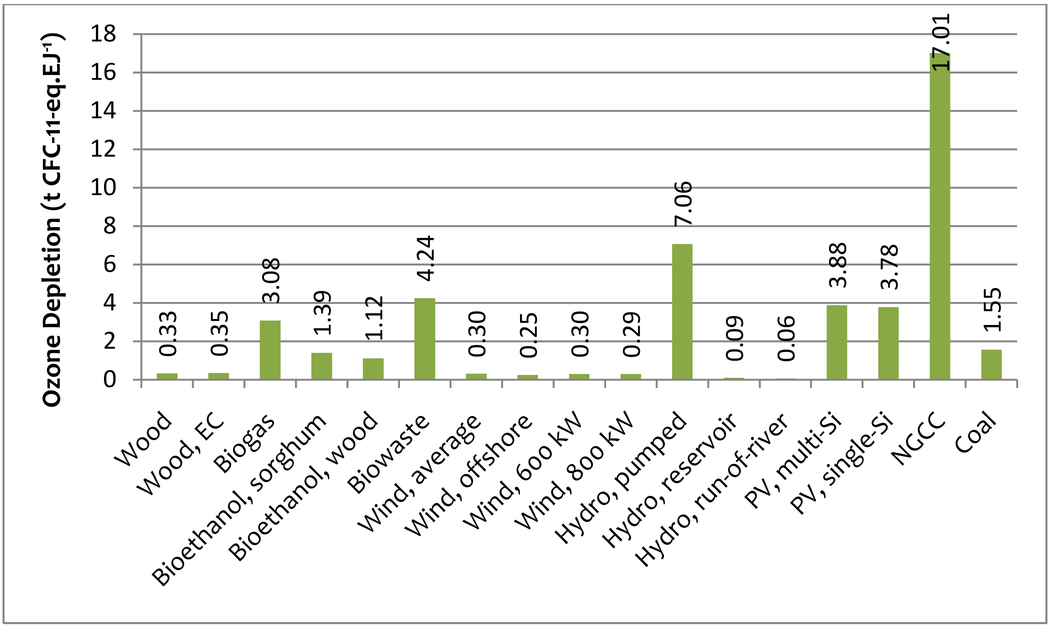

Figure 4.4: Emissions of CFC-11-eq (ozone depletion potential) from renewable and non-renewable energies.

Other Emissions

Marine and freshwater eutrophication had the same magnitude for all processes studied, so they were amalgamated into the same column. Coal, natural gas and biogas all showed quite high values for these impact categories.

The general observation with the remaining emissions is that with the exception of terrestrial ecotoxicity and ionising radiation, coal has the highest impact of all the processes studied. The pumped reservoir hydropower facility had by far the highest impact in ionising radiation; however, a double check of the raw data shows that this is not an error. Biogas also demonstrated an exceptionally high value for ionising radiation. It is uncertain what the cause of these extraordinarily high values is. Biogas, the combustion of biomass and the pumped reservoir hydropower in general seem to have the highest impact of all the renewable energy sources examined. Due to the pumped reservoir's dependence on fossil fuels, this is not surprising.

Table 4.1: Summary of emissions from renewable and non-renewable energy technologies. Quantities emitted per EJ.

[1] Terr. –Terrestrial; PCOF = Photochemical Oxidant Formation; FW= Freshwater	Climate Change (Mt CO_2-eq)	PM Formation (kt PM10)	Terr. Acid. (kt SO_2-eq)	O_3 Depletion (kg CFC-11-eq)	Human Toxicity	Ionising Radiation (kt U235-eq)	PCOF (kt NMVOC)	Terr. Ecotoxicity (kt 1,4-DCB-eq)	Marine Ecotoxicity (kt 1,4-DCB-eq)	FW Ecotoxicity (kt 1,4-DCB-eq)	Marine /FW Eutrophication (Mt N-eq)
Wood	3.7	82.2	79.3	326	20.6	817	125	208	101	74.1	3.9
Wood, EC	10.7	30.1	95.0	346	20.7	831	73.9	208	102	74.9	10.7
Biogas	71.3	50.6	219	3082	5.5	12061	120	1.5	112	105	151
Bioethanol, sorghum	19.9	91.2	228	1389	14.8	7105	148	388	204	1012	20.6
Bioethanol, wood	10.6	28.0	83.2	1117	7.4	918	70.7	66	59	49.1	11.1
Biowaste	40.8	159	388	4244	66.8	5548	685	10	976	1135	43.4
Wind, average	4.8	14.4	20.7	304	5.1	917	15.6	0.6	179	169	5.4
Wind, offshore	4.0	10.2	15.7	249	3.4	638	13.0	0.4	106	101	4.4
Wind, 600 kW	4.8	14.8	20.8	298	5.0	943	15.4	0.7	190	180	5.4
Wind, 800 kW	4.4	12.8	18.6	285	4.5	823	14.2	0.6	150	142	5.0
Hydro, pumped	52.5	80.4	211.9	7063	37.1	277025	119	6.8	705	681	57.1
Hydro, reservoir	1.5	4.6	4.1	86.0	0.3	374	5.3	0.1	14	13.4	1.7
Hydro, run-of-river	1.0	5.7	3.5	64.4	0.3	207	4.7	0.1	11	10.5	1.0
PV, multi-Si	18.0	29.3	75.8	3882	24.2	4679	69.0	39.3	389	305	20.0
PV, single-Si	20.0	31.7	84.4	3780	25.5	6706	71.2	37.3	416	337	22.0
NGCC	118	30.3	88.7	17013	0.9	312	128	2.0	48	19.8	131
Coal	300	383	1270	1554	89.3	4856	719	3.5	1974	2004	342

The general trend through all of the analyses performed appears to be that combustion of primary fuels results in higher impacts.

4.2 Land Requirements

Critics of renewable energies argue that the relatively low energy intensity of these energy sources require that renewable energy power plants consume larger quantities of land than is practical. This land, being used for energy production, would then be unavailable to other activities that are perhaps more necessary or economically viable, such as farming. The results of this study show, however, that the non-renewable energies have the highest values in land transformation of all the processes studied (Figure 4.5). Furthermore, in total land occupation, encompassing both agricultural and urban land occupation, coal has the highest value other than the wood combustion and bioethanol technologies.

The raw results from land use are presented in Table 4.2 It is interesting to note that the run-of-river hydropower project has a negative value for land transformation. It is possible that the ecoinvent model for this process includes the transformation of land back to its natural state from a non-natural land use. This is represented by a negative characterization factor in ReCiPe (Goedkoop, Heijungs et al. 2009). Given that run-of-river hydropower projects do not otherwise transform land, then the negative characterization factor would be reflected in the results.

These results are logical when the consequences of these processes are considered. In the case of coal and natural gas, the land transformation is high due to the intensive mining and extraction techniques used to obtain these fuels. The bioenergies, with the exception of biowaste, have the highest land transformation values among the renewable energy sources, with the exception of the pumped reservoir hydropower. The agricultural and harvesting activities attributed to the sorghum and wood feedstocks, respectively, detracts land from its natural state. The reservoir hydropower technologies flood significant areas of land, which is frequently wilderness, or natural land, prior to the project being implemented. The result is relatively high values for land transformation. This is true for the pumped reservoir hydropower technology, as additional land is transformed for the extraction o fossil fuels used to power the pump, and possibly also due to the fact that these facilities

Table 4.2: Summary of land use for renewable and non-renewable energies.

	Total Land Occupation ($km^2 \cdot a$)	Land Transformation (km^2)
Wood	18880	2.52
Wood, EC	18927	2.57
Biogas	358	5.86
Bioethanol, sorghum	40332	3.18
Bioethanol, wood	81794	8.25
Biowaste	1009	1.16
Wind, average	638	0.51
Wind, offshore	103	0.53
Wind, 600 kW	556	0.50
Wind, 800 kW	445	0.47
Hydro, pumped	1046	9.45
Hydro, reservoir	35	2.36
Hydro, run-of-river	24	-0.03
PV, multi-Si	849	3.48
PV, single-Si	841	3.57
NGCC	76	26.22
Coal	8328	14.05

also often have two reservoirs; that from which the power is generated, and another where the water is collected prior to being pumped to the upper reservoir again.

These results are logical when the consequences of these processes are considered. In the case of coal and natural gas, the land transformation is high due to the intensive mining and extraction techniques used to obtain these fuels. The bioenergies, with the exception of biowaste, have the highest land transformation values among the renewable energy sources, with the exception of the pumped reservoir hydropower. The agricultural and harvesting activities attributed to the sorghum and wood feedstocks, respectively, detracts land from its natural state. The reservoir hydropower technologies flood significant areas of land, which is frequently wilderness prior to the project being implemented. The result is relatively high values for land transformation. This is true for the pumped reservoir hydropower technology, as additional land is transformed for the extraction o fossil fuels used to power the pump, and possibly also due to the fact that these facilities also often have two reservoirs; that from which the power is generated, and another where the water is collected prior to being pumped to the upper reservoir again.

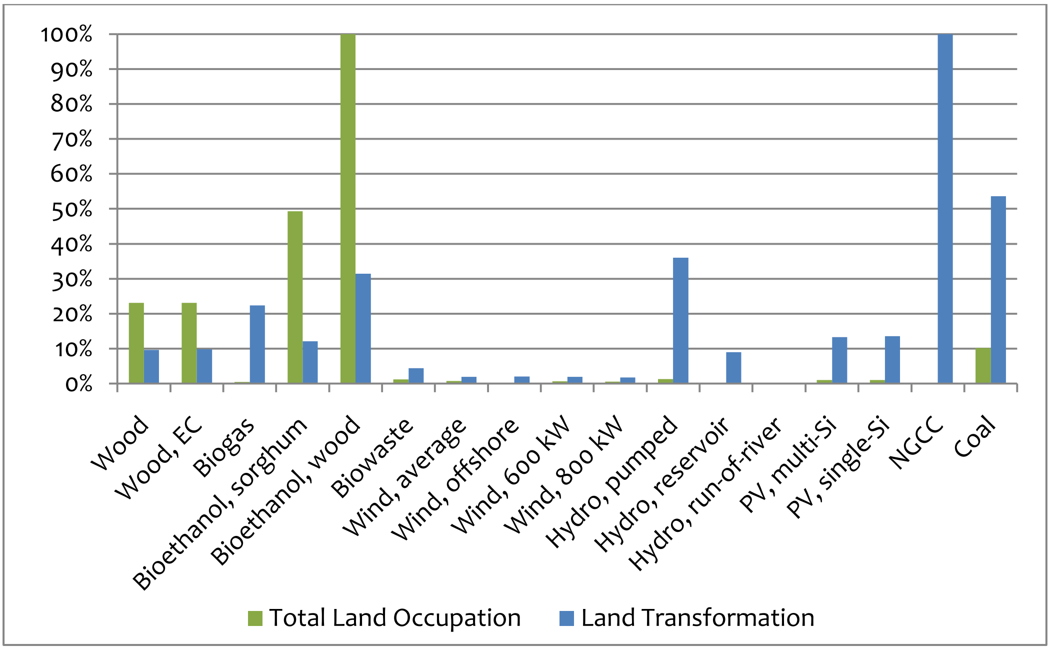

Figure 4.5: Land transformation and total land use for renewable and non-renewable energy technologies.
Results are normalized using the highest value in each category.

The situation with land occupation is similar to that of land transformation. With the biomass-derived energy sources, the wood feedstocks and the sorghum bioethanol have the highest values for total land occupation, as energy is considered the primary product of the cultivation of these crops. as a result, the land occupied by the crops is allocated to these energy processes. Because biogas and biowaste energy is derived from waste products such as manure and leftover commercial food waste, the land occupation (and other emissions) attributable to the production of the biomass has been allocated to other processes such as beef, milk or food production.

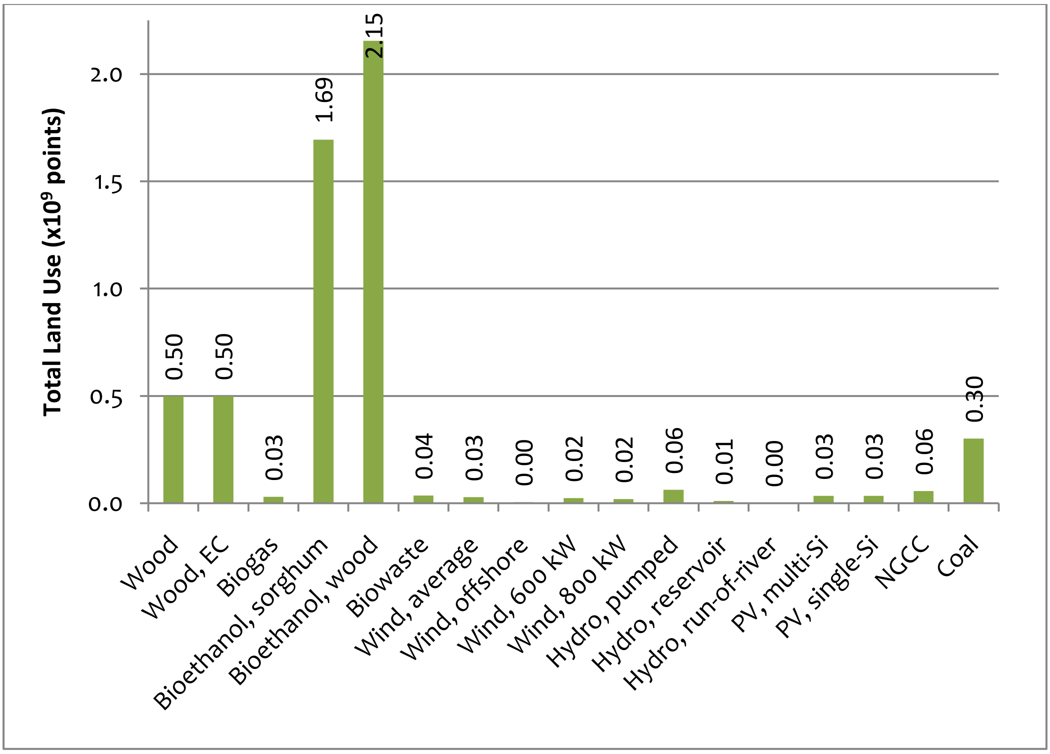

Figure 4.6: Total land use impact for renewable and non-renewable energy technologies in terms of single-score endpoint indicator

The conclusion that can be reached from this analysis of land use is that renewable energy technologies are still competitive (Figure 4.6). While it may be true that renewable energy power plants occupy and transform more land than conventional fossil fuel facilities, when the entire life cycle is considered, the fossil fuel technologies also consume significant areas of land. Furthermore, despite biomass-derived energies consuming the most land in terms of absolute points, as shown in Figure 4.6, it should not be forgotten that their use of the land is of a lesser severity than that for the fossil fuels. As an example, a field of sorghum would continue to sequester CO2, albeit temporarily, would likely not deviate far from the land's natural state, and is more aesthetically pleasing than an open-pit coal mine.

4.3 Overall Impact

Figure 4.7 shows the results from the single-score endpoint indicator for all of electricity production technologies reviewed. As one might expect, the two technologies with the highest impact are the non-renewable processes, natural gas and coal combustion. From the results observed, one can conclude that bioenergy, with the exception of pumped reservoir hydropower facility, have the highest impact of the renewable energies examined. This is followed by solar photovoltaic technology followed by wind and hydro, respectively.

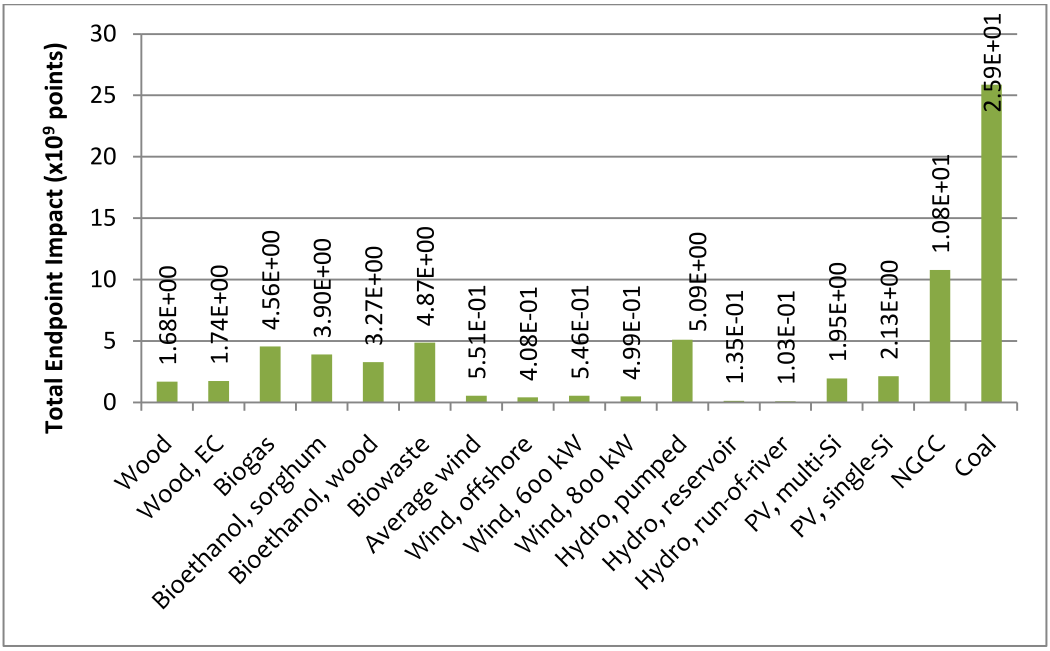

Figure 4.7: Total impact of energy technologies using single-score endpoint.

4.4 Material Demand

The material demands of all of the processes studied is shown in Figure 4.8. It is clear that in all processes with the exceptions of wood combustion and bioethanol from sorghum, the waste category is the most significant source of material flow. For further detail, Figure 4.9 to Figure 4.14 show the renewable energies together in groups. In these figures, the waste sector was removed in order to provide greater detail for the remaining sectors. For the most part, the different technologies used to produce electricity from a given renewable energy source show very similar resource use.

One exception to this pattern, however, is bioenergy (Figure 4.9); as expected, the dominant area of material flow occurs with the feedstock of the technology – either wood or sorghum. In the case of biogas and biowaste, the feedstock is considered to be the waste from other processes and therefore not allocated to the process. However, one can see that bioethanol from sorghum requires a significantly greater material flow from the agriculture sector than the wood-based technologies required from the wood sector. This is likely due to the intensive farming processes required for the production of the sugar crop.

With wind energy, the most significant areas of material flow lie in the Metals and Mining/Minerals sectors (Figure 4.10). These are likely related to the construction of the turbine itself, which is heavy in concrete/cement and metal. Fuels also play a considerable role, likely attributable to the energy intensive materials such as steel and aluminium (Jungbluth, Bauer et al. 2005; Jungbluth, Stucki et al. 2009).

The three hydroelectricity technologies examined generally show the same trends with one notable exception: in the pumped hydropower, fuels are over half of the material flow (when the waste sector is excluded, Figure 4.11). Since the reservoir water is continuously pumped back up to the upper reservoir, this is not unexpected. If the fuel portion were to be removed from the pumped hydropower technology, the result would be quite similar to the reservoir and run-of-river technologies. Since the run-of-river technology does not involve the construction of a dam, which is material intensive, the overall mass of materials used is less. This is reflected in the Mining/Minerals sector, which the concrete and cement used in dam construction is classified.

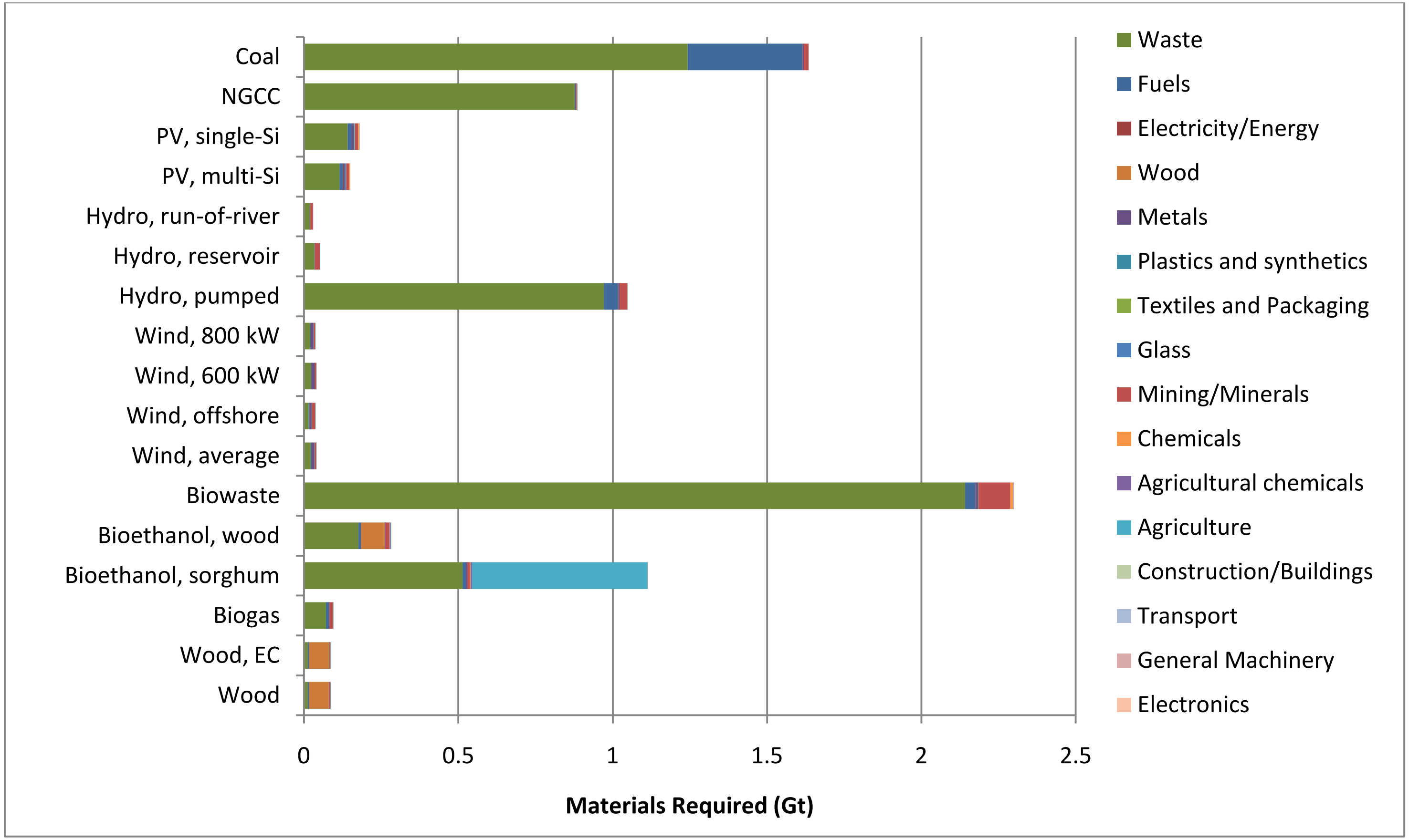

Figure 4.8: Overview of material use in energy technologies according to aggregation categories, for production of 1 EJ of electricity.

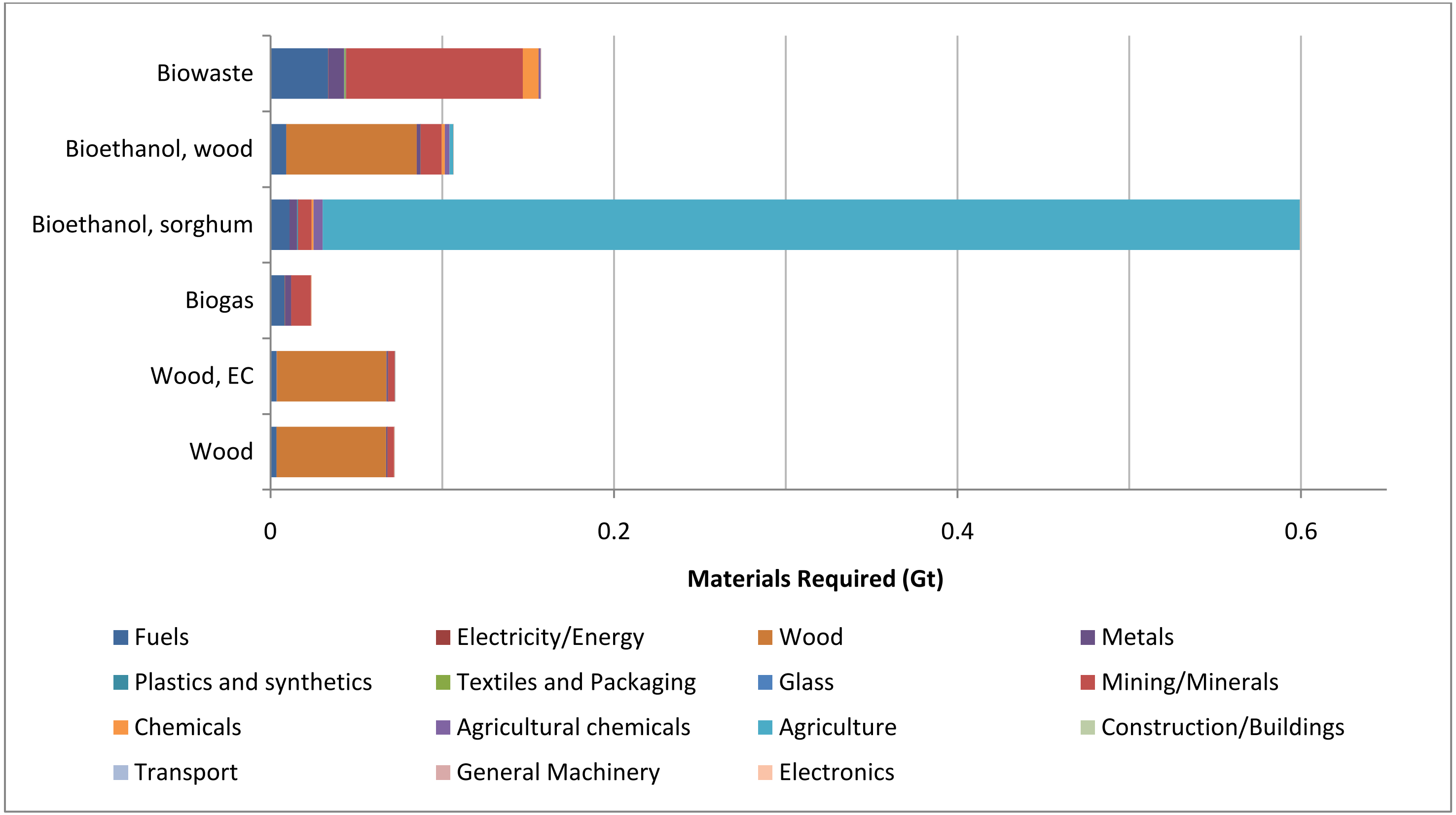

Figure 4.9: Material consumption in bioenergy technologies for production of 1 EJ of electricity, excluding waste.

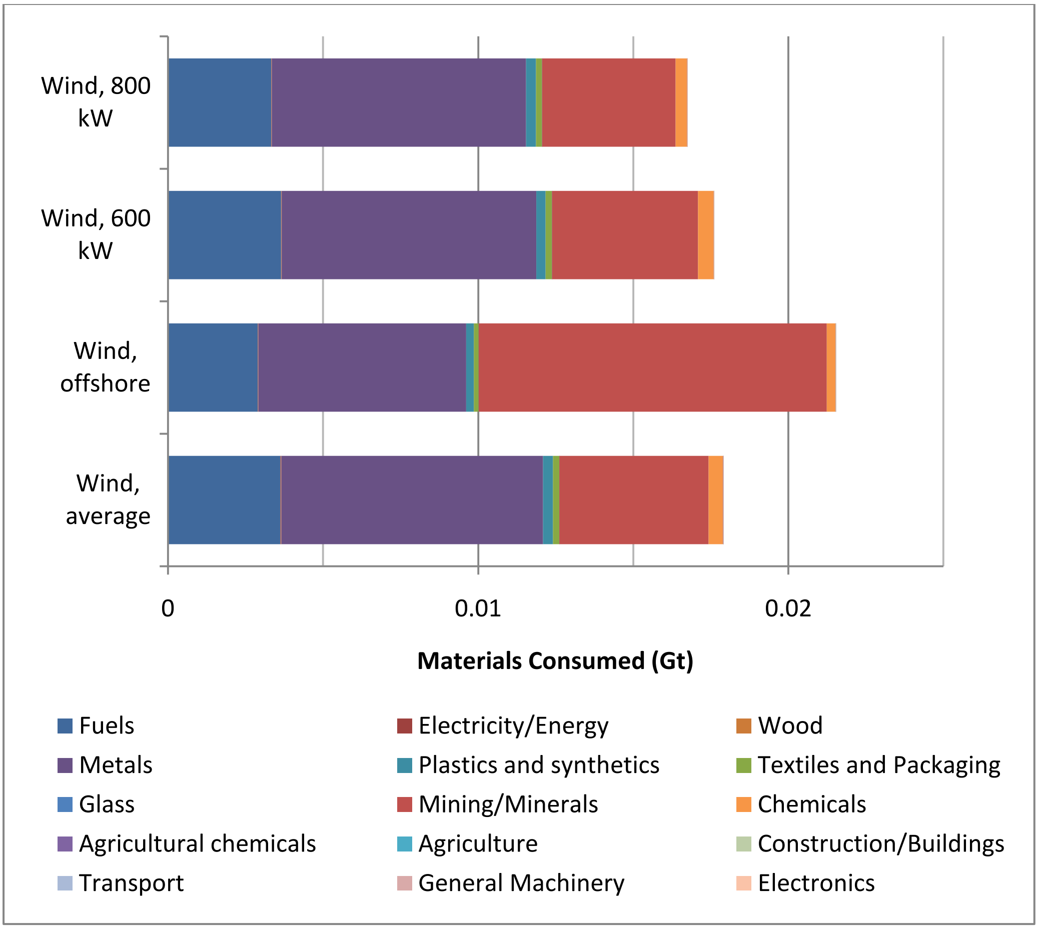

Figure 4.10: Material consumption in wind power technologies for production of 1 EJ of electricity, excluding waste.

Similarly, the solar PV technologies are intensive in Metals, Mining/Minerals and Fuels sectors (Figure 4.12), as silicon is the dominant material in the PV cells. The purification of silicon for the manufacture of PV cells is also quite energy intensive (Jungbluth, Bauer et al. 2005). Chemicals play a role in material demand for PV cells, likely associated with the processing of the silicon for the cell, which involves a dyeing process and doping process (Jungbluth, Bauer et al. 2005; Letcher 2008). Glass, which is typically as a protective cover for the PV cell, also plays a small role in material consumption (Jungbluth, Bauer et al. 2005; Letcher 2008; Jungbluth, Stucki et al. 2009).

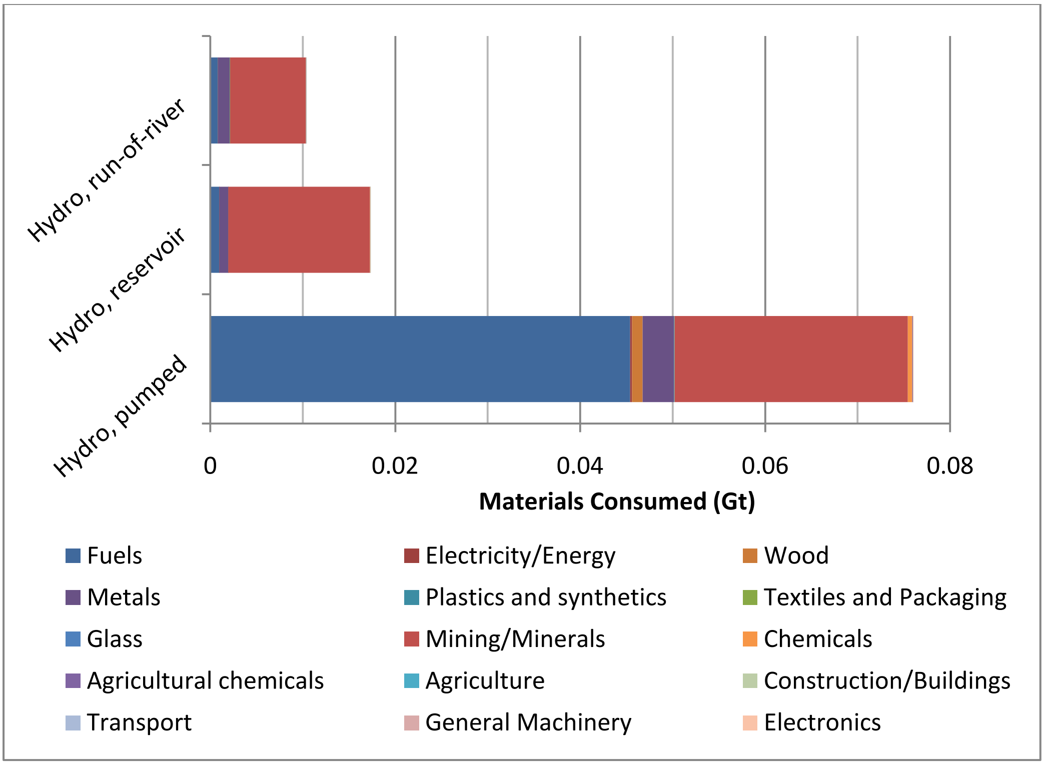

Figure 4.11: Material consumption in hydropower technologies for production of 1 EJ of electricity, excluding waste.

Interesting trends are observable in the non-renewable processes. In coal combustion, the fuel mass far outweighs the other materials consumed in the lifetime of the coal power plant (Figure 4.14). On the other hand, in the natural gas combined cycle facility, material consumption is spread nearly equally over Fuels, Metals and Mining/Minerals (Figure 4.13). The latter two sectors are likely due to the construction of the plant infrastructure, while Fuels is, of course, mostly attributable to the natural gas consumed as feedstock over the lifetime of the facility. The reason coal plants might have such a high percentage of life cycle material consumption could be due to the low energy density of coal relative to natural gas (Ausubel 2007).

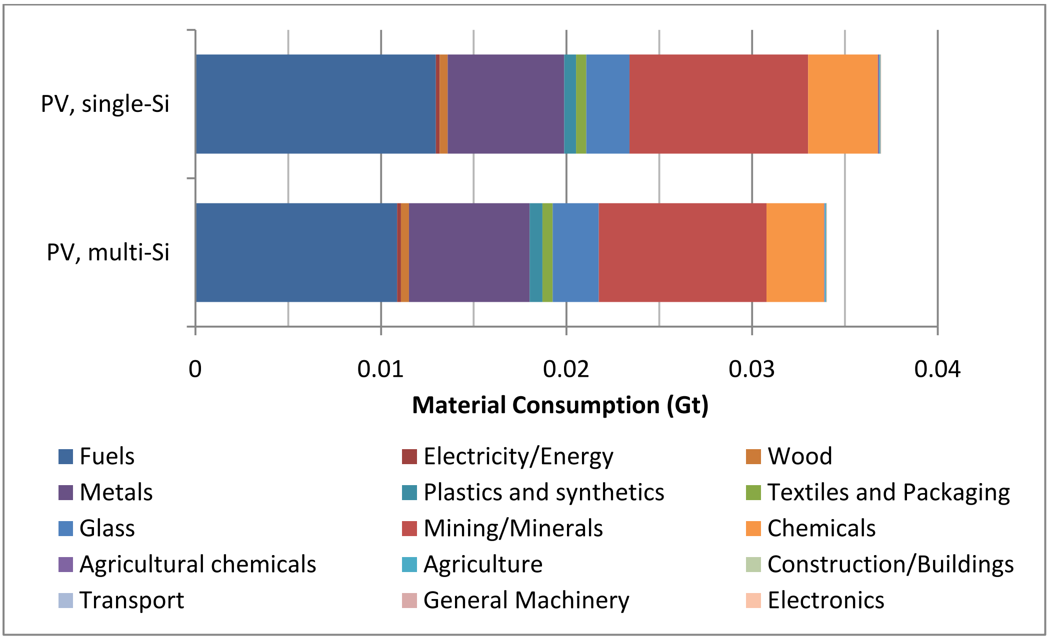

Figure 4.12: Material consumption in solar photovoltaic technologies for production of 1 EJ of electricity, excluding waste.

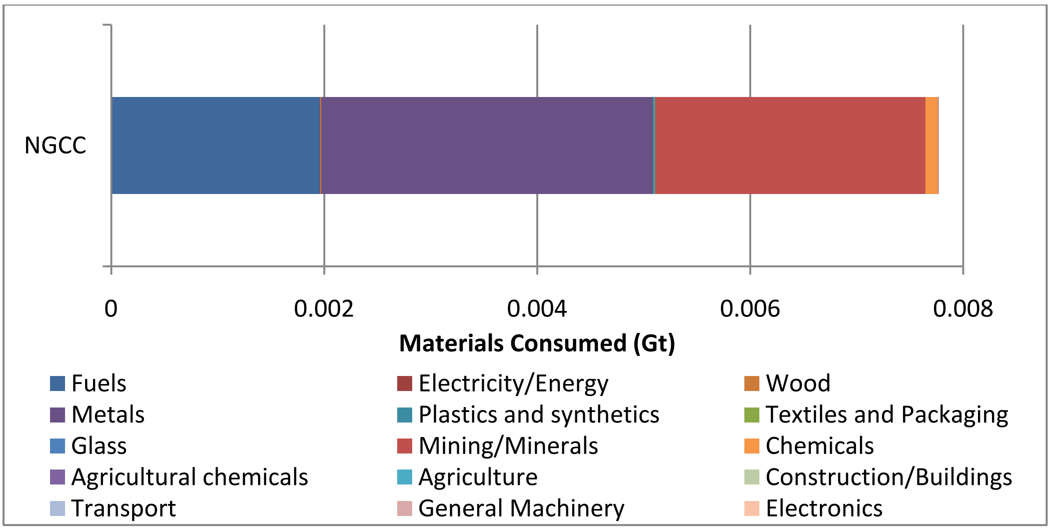

Figure 4.13: Material consumption in natural gas combined cycle power plants for production of 1 EJ of electricity, excluding waste.

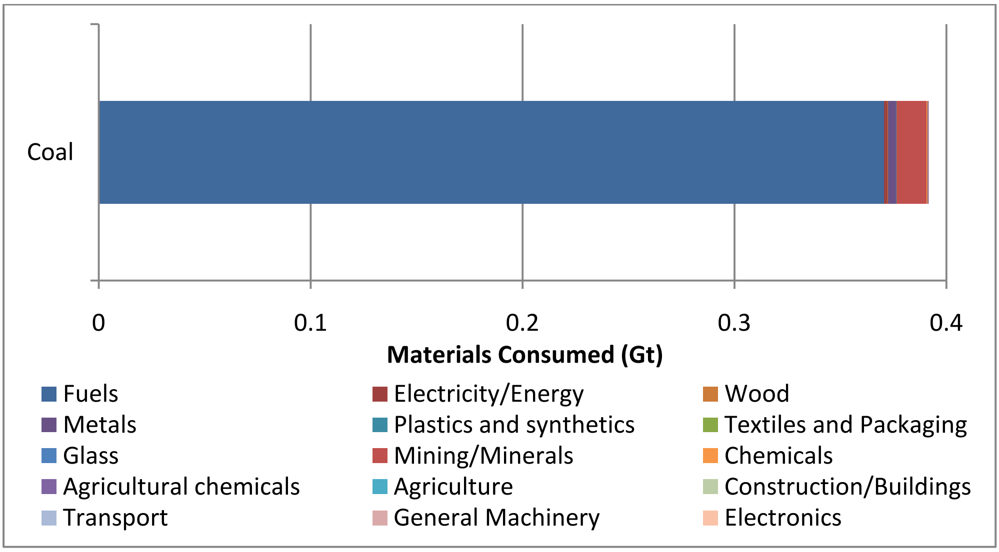

Figure 4.14: Material consumption in hard coal power plants for production of 1 EJ of electricity, excluding waste.

4.5 Impact from Material Use

Figure 4.15 to Figure 4.18 show the contribution of materials on the four midpoint impact categories explored in further detail in §4.1. Here we can see that materials play a strong role in the climate change impact for the bioethanol and biowaste processes, the wind processes, the reservoir and run-of-river hydropower and the solar photovoltaics (Figure 4.15). Much of the impacts are due to Metals, and Mining and Minerals, with plastics and synthetics also playing a role in the wind turbines. In the other energy processes, materials play a nearly insignificant role, contributing to less than 10% of total climate change impact. It worth noting that the climate change impact of agricultural chemicals, i.e. fertilizers, is very much evident in the sorghum bioethanol process.

For particulate matter formation, it is very much a familiar scene: the biogas, wood, pumped reservoir hydropower and fossil fuels have about or less than 10% contribution to PM10 formation attributed to materials (Figure 4.16). This may be because these processes involve combustion of relatively 'unclean' fuels which emit significant quantities of greenhouse gases and particulate matter over their lifetime.

As a result, the one-time impact of material use in infrastructure plays a relatively small role over the entire lifetime of the facility. The difference here is that the metals play a much larger role here than the plastics and synthetics, especially in the wind turbines. This is likely due to the dependence of metalsmithing on open fire requiring combustion of fossil fuels.

In the acidifying emissions, sorghum bioethanol has the highest proportion of material contributions than all other processes (Figure 4.17). It is overwhelmingly the agriculture sector which contributes this impact. It may be that the acidic hydrolysis products are assigned to this sector, thus taking the nearly half of the acidifying potential of the entire process. Again, wind and photovoltaics have 30-50% of their acidifying impact attributed to materials. For the wind turbines, this is split nearly evenly between metals and plastics and synthetics. Nearly all processes show a visible portion of their acidifying potential that is due to chemicals. This is likely attributable to acids being used in various treatment processes for the materials used in the infrastructure for the processes.

Finally, the ozone depleting emissions (Figure 4.18) tell a very different story; all of the processes with the exception of biogas, pumped reservoir hydropower and natural gas have the vast majority of their impact in this category attributable to materials. Furthermore, these impacts can specifically be pinpointed to fuels and chemicals. For solar photovoltaic, the plastics and synthetics also play a significant role. One explanation for this phenomenon is that the previous three impact categories are predominantly results of combustion processes. While ozone depleting NOx emissions may be formed in combustion processes, it is unusual for controlled burns as found in industry.

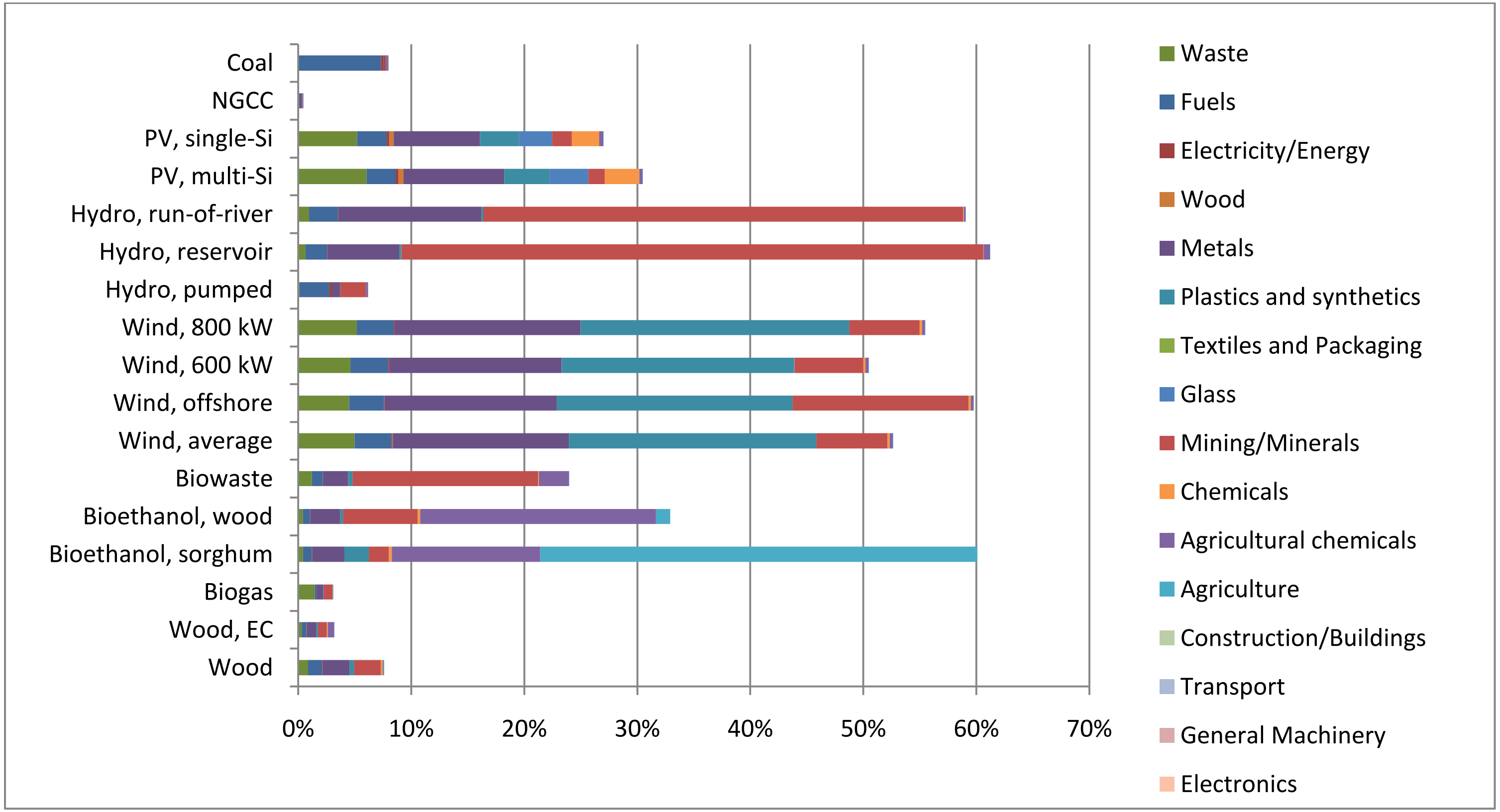

Figure 4.15: Climate change emissions attributable to materials production in renewable and non-renewable energy technologies.

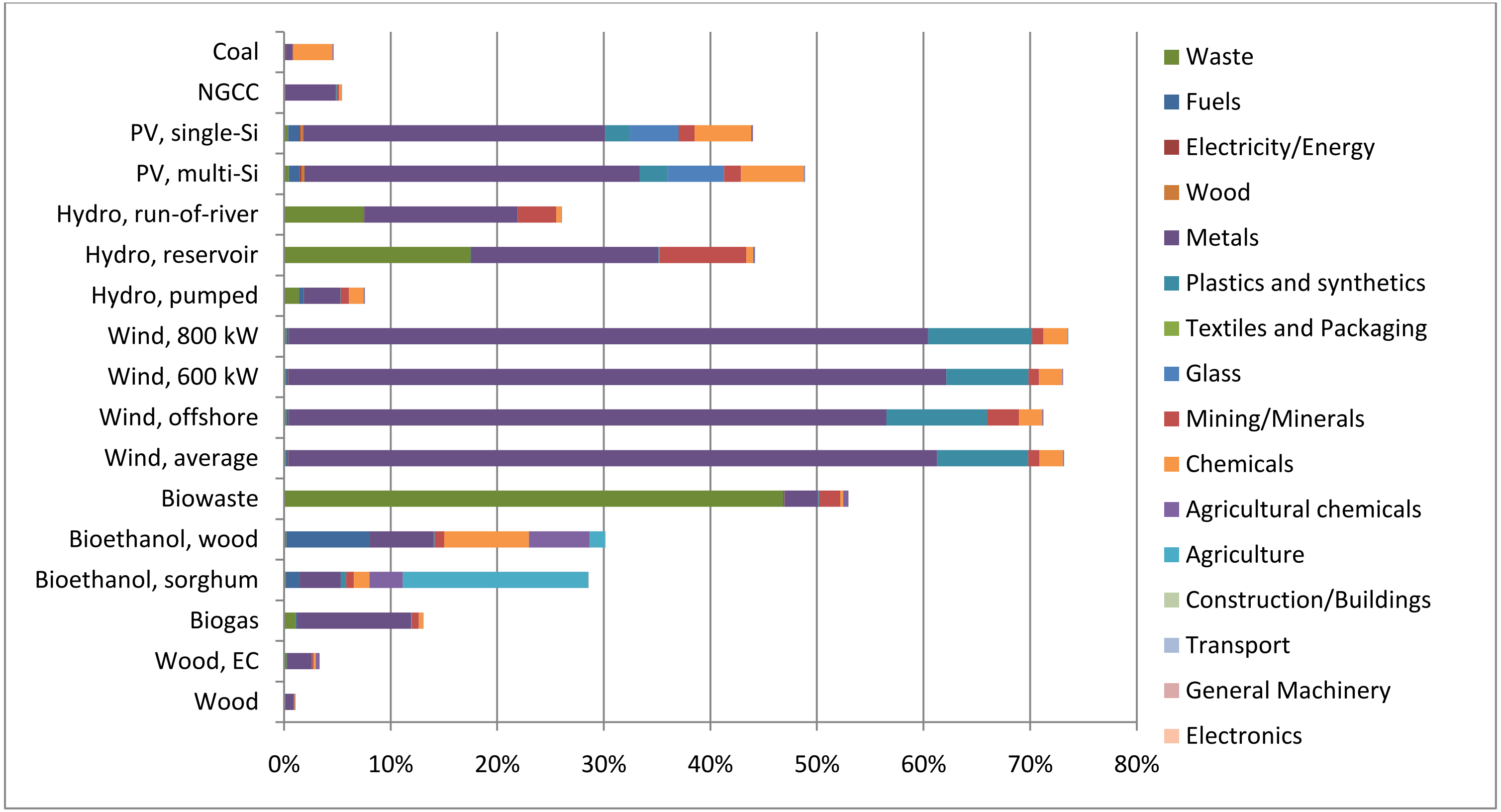

Figure 4.16: PM10 emissions attributable to materials production in renewable and non-renewable energy technologies.

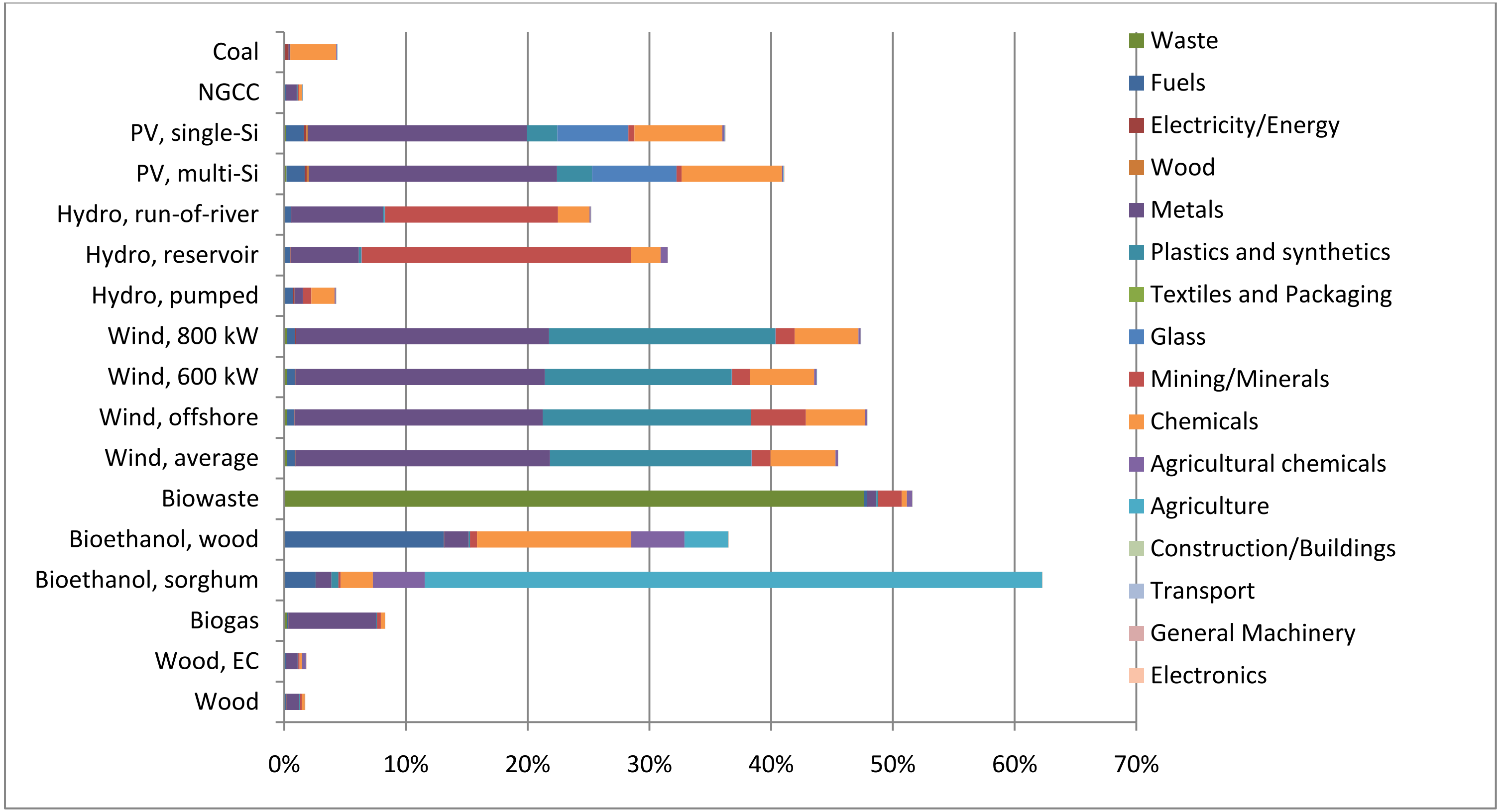

Figure 4.17: Acifidifying emisions attributable to materials production for renewable and non-renewable energy technologies.

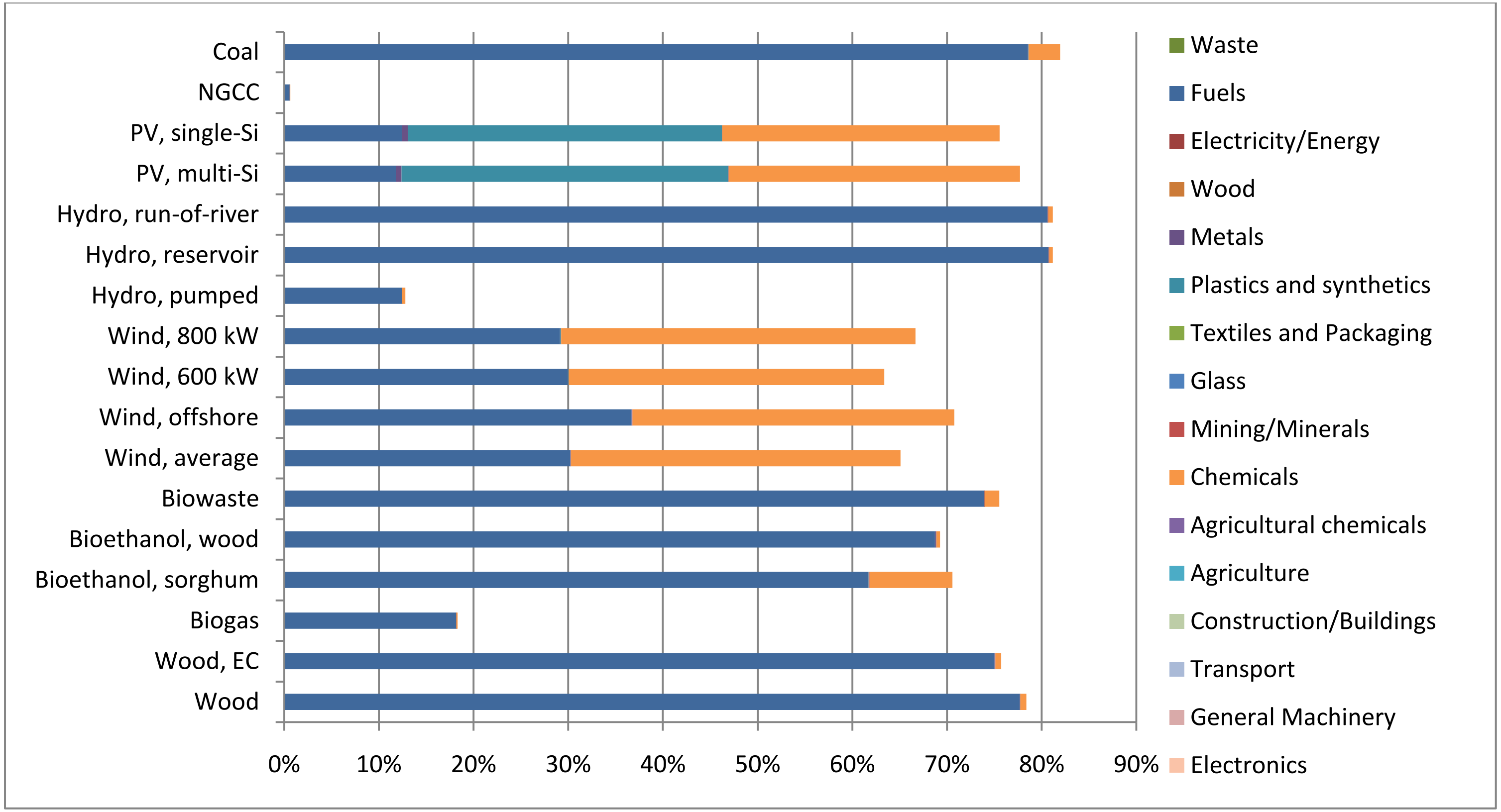

Figure 4.18: Ozone depleting emissions attributable to materials production for renewable and non-renewable energy technologies.

4.6 Contributions from Life-Cycle Steps

The results from the geometric series expansion, sorted by energy source, are shown in Figure 4.19 to Figure 4.23. The results from each graph are interpreted in conjunction with the SPA results. The SPA will largely reflect the results from the geometric series expansion. Since it was observed in the geometric series expansion that most of the large "jumps" in impact contributions occur in the first ten tiers of every process studied, for the sake of conciseness in the body of this report, only the top ten ranked paths will be included. In addition, for the cases where multiple technologies for the same energy source showed similar behaviour in the geometric series expansion, the SPA results of only one of these technologies is presented. A complete presentation of the SPA results, including a tabulation of the top 25 ranked paths may be found in the the Appendix and in the Excel file 'amalgamated Results.xls.' Note that the process studied, or the zeroeth tier, has been removed from the paths for presentation purposes.

Bioenergy

As one might expect from previous results obtained, the bioenergy technologies are somewhat disparate due to significant differences in the processes (Figure 4.19). The wood combustion processes are nearly identical, with an initial steep climb in the curve, indicating heavy impact contribution from the zeroeth and first tiers. The curve flattens before another sharp increase occurs in tiers 6 and 7.

The SPA results can indicate much regarding the trends observed in Figure 4.19. For the wood combustion process, the majority of the impacts stem from the combustion process itself. The remaining paths involve the disposal of the wood ash through various means such as landfarming, sanitary landfill and municipal incineration, the harvesting of the wood, the transport of the wood by road, and the combustion of fossil fuels.

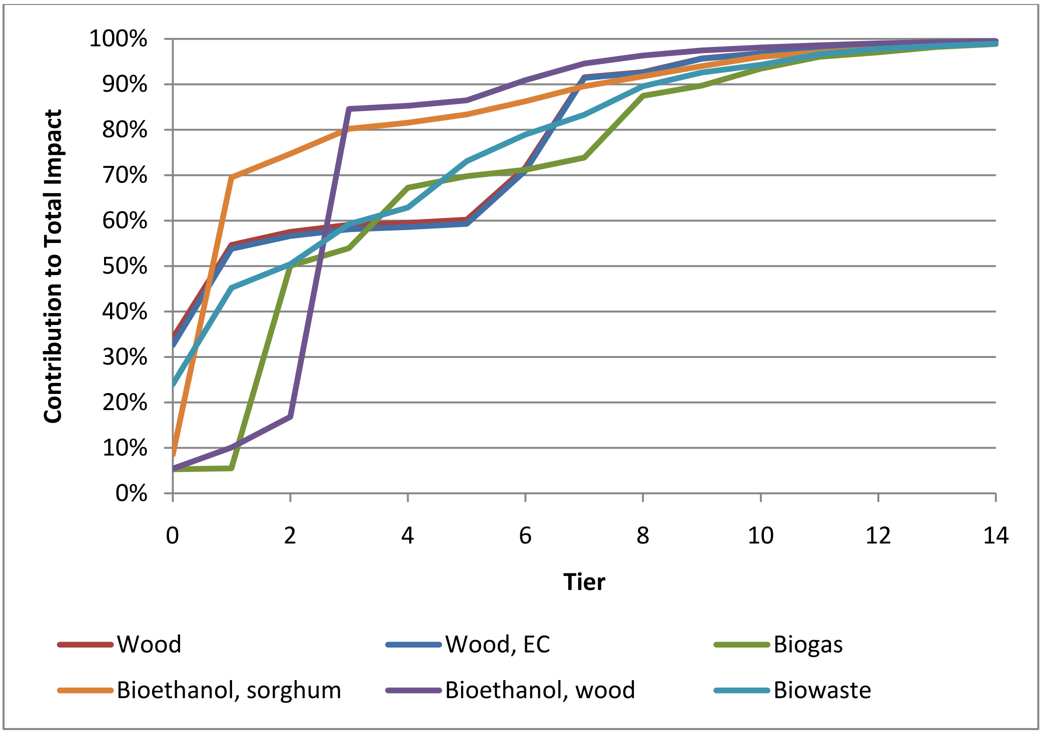

Figure 4.19: Cumulative contribution to total impact of bioenergies as a function of tier number.

Table 4.3: Structural path analysis results for wood combustion process

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence(Wood→)
1	0	32.60	
2	7	16.77	wood chips, mixed, from industry, at plant → wood chips, softwood, from industry, at plant → industrial residue wood, mix, softwood, at plant → industrial residue wood, softwood, forest-debarked, at plant → round wood, softwood, debarked, u=70% at forest road → round wood, softwood, under bark, u=70% at forest road → softwood, standing, under bark, in forest
3	1	15.63	disposal, wood ash mixture, pure, 0% water, to landfarming
4	6	10.44	wood chips, mixed, from industry, at plant → wood chips,

			hardwood, from industry, at plant → industrial residue wood, mix, hardwood, at plant → industrial residue wood, hardwood, including bark, at plant → round wood, hardwood, under bark, at forest road → hardwood, standing, under bark, in forest
5	1	3.55	disposal, wood ash mixture, pure, 0% water, to sanitary landfill
6	2	2.71	transport, lorry 20-28t, fleet average → operation, lorry 20-28t, fleet average
7	1	1.81	disposal, wood ash mixture, pure, 0% water, to municipal incineration
8	3	0.61	cogen unit 6400kWth, wood burning, components for electricity only → control cabinet cogen unit 160kWe → light fuel oil, burned in industrial furnace 1MW, non-modulating
9	7	0.51	wood chips, mixed, from industry, at plant → wood chips, softwood, from industry, at plant → industrial residue wood, mix, softwood, at plant → industrial residue wood, softwood, forest-debarked, at plant → round wood, softwood, debarked, u=70% at forest road → round wood, softwood, under bark, u=70% at forest road → softwood, stand establishment / tending / site development, under bark
10	3	0.45	cogen unit 6400kWth, wood burning, components for electricity only → control cabinet cogen unit 160kWe → natural gas, burned in industrial furnace >100kW

The bioethanol from sorghum process is much simpler, with all of the top ten paths having lengths less than 4 processes long (Table 4.4). By far the most significant impact is from the production of the sorghum biomass, which causes the sharp increase in the curve observed in Figure 4.19. The remaining top contributions stem from farming activities at the sorghum plantation, production of nitrogen compounds for fertilizer, disposal of ash, and transport.

Table 4.4: Structural path analysis results for bioethanol from sorghum process

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence(Bioethanol, sorghum→)
1	1	55.01	sweet sorghum stem, at farm
2	0	8.56	
3	1	4.33	disposal, wood ash mixture, pure, 0% water, to landfarming
4	3	1.94	sweet sorghum stem, at farm → ammonium nitrate, as N, at regional storehouse → nitric acid, 50% in H2O, at plant
5	3	1.38	sweet sorghum stem, at farm → irrigating → polyethylene, HDPE, granulate, at plant
6	2	1.31	sweet sorghum stem, at farm → combine harvesting
7	2	1.16	transport, lorry >16t, fleet average → operation, lorry >16t, fleet average
8	2	0.99	sweet sorghum stem, at farm → tillage, ploughing
9	1	0.98	disposal, wood ash mixture, pure, 0% water, to sanitary landfill
10	3	0.61	sweet sorghum stem, at farm → urea, as N, at regional storehouse → ammonia, steam reforming, liquid, at plant

Table 4.5: Structural path analysis results for bioethanol from wood process

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence(Bioethanol, wood→)
1	3	62.48	wood chips, hardwood, u=80%, at forest → industrial wood, hardwood, under bark, u=80%, at forest road → hardwood, standing, under bark, in forest
2	0	5.44	
3	2	2.42	ammonia, liquid, at regional storehouse → ammonia, steam reforming, liquid, at plant
4	1	2.40	disposal, wood ash mixture, pure, 0% water, to landfarming
5	2	2.25	transport, lorry 20-28t, fleet average → operation, lorry 20-28t,

			fleet average
6	3	1.71	wood chips, hardwood, u=80%, at forest → industrial wood, hardwood, under bark, u=80%, at forest road → hardwood, stand establishment / tending / site development, under bark
7	3	1.67	wood chips, hardwood, u=80%, at forest → wood chopping, mobile chopper, in forest → diesel, burned in building machine
8	1	0.83	quicklime, in pieces, loose, at plant
9	2	0.81	ammonia, liquid, at regional storehouse → ammonia, partial oxidation, liquid, at plant
10	2	0.73	maize starch, at plant → grain maize IP, at farm

Comparing now the bioethanol from wood, it is evident that this process is also rather 'shallow;' most of the contributions occur in the top three tiers. Again, road transport and nitrogen fertilizer ingredients make an appearance and the activities associated with managed forests take the place of the farming activities observed for the sorghum ethanol. Also, in lieu of the disposal processes seen in the sorghum bioethanol, two of the top ten paths in the wood ethanol process are quicklime and grain maize destined for starch at the bioethanol plant.

Table 4.6: Structural path analysis results for biowaste process

Path Rank	**Path Length**	**Contribution to Total Impact (%)**	**Path Sequence(Biowaste→)**
1	0	24.02	
2	1	11.96	transport, municipal waste collection, lorry 21t
3	1	8.05	process-specific burdens, municipal waste incineration
4	2	2.47	process-specific burdens, municipal waste incineration → natural gas, burned in industrial furnace low-NOx >100kW
5	3	2.32	cement, unspecified, at plant → portland calcareous cement, at plant → clinker, at plant
6	3	2.13	cement, unspecified, at plant → portland cement, strength class Z 42.5, at plant → clinker, at plant
7	5	1.54	transport, municipal waste collection, lorry 21t → diesel, at regional storage → diesel, at refinery → crude oil, production RaF, at long distance transport → crude oil, at production

			onshore
8	2	1.14	transport, lorry 20-28t, fleet average → operation, lorry 20-28t, fleet average
9	5	1.13	transport, municipal waste collection, lorry 21t → diesel, at regional storage → diesel, at refinery → crude oil, production RME, at long distance transport → crude oil, at production onshore
10	5	1.05	transport, municipal waste collection, lorry 21t → diesel, at regional storage → diesel, at refinery → crude oil, production NG, at long distance transport → crude oil, at production

Again, the biowaste results are quite simple (Table 4.6). However, since the biowaste is considered a waste product from another process, there are no impacts attributed to its growth as biomass. The biowaste combustion itself contributes 24% to the total impact, and the third and fourth highest impacts come from incineration processes. The majority of the remaining processes in the ten most significant paths are concerned with diesel, whether it is the operation of the truck or the production of the fuel for the trucks. Two processes are related to the manufacture of cement for the incineration centre infrastructure.

Table 4.7: Structural path analysis results for biogas combustion process

Path Rank	**Path Length**	**Contribution to Total Impact (%)**	**Path Sequence (Biogas→)**
1	2	39.89	biogas, production mix, at storage → biogas, from biowaste, at storage
2	4	12.43	biogas, production mix, at storage → biogas, from sewage sludge, at storage → heat, natural gas, at boiler condensing modulating >100kW → natural gas, burned in boiler condensing modulating >100kW
3	0	5.29	
4	2	4.69	biogas, production mix, at storage → biogas, from sewage sludge, at storage
5	8	4.40	biogas, production mix, at storage → biogas, from sewage sludge, at storage → heat, natural gas, at boiler condensing modulating

			>100kW → natural gas, burned in boiler condensing modulating >100kW → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production RU, at long-distance pipeline → natural gas, at production onshore
6	8	2.15	biogas, production mix, at storage → biogas, from sewage sludge, at storage → heat, natural gas, at boiler condensing modulating >100kW → natural gas, burned in boiler condensing modulating >100kW → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production NL, at long-distance pipeline → natural gas, at production onshore
7	8	2.13	biogas, production mix, at storage → biogas, from sewage sludge, at storage → heat, natural gas, at boiler condensing modulating >100kW → natural gas, burned in boiler condensing modulating >100kW → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production NO, at long-distance pipeline → natural gas, at production offshore
8	3	1.88	biogas, production mix, at storage → biogas, from biowaste, at storage → transport, municipal waste collection, lorry 21t
9	8	1.18	biogas, production mix, at storage → biogas, from sewage sludge, at storage → heat, natural gas, at boiler condensing modulating >100kW → natural gas, burned in boiler condensing modulating >100kW → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production DZ, at long-distance pipeline → natural gas, at production onshore
10	3	0.92	biogas, production mix, at storage → biogas, from biowaste, at storage → disposal, municipal solid waste, 22.9% water, to municipal incineration

Wind

The wind technologies (Figure 4.20) share the same general shape, with a gradually increasing curve towards the processes further in the background. The most significant process is the manufacture of fibreglass. At the same tier is the manufacture of primary copper for the moving parts of the turbine. Although the path with the most impact is the fixed parts for the turbine, the majority of the remaining top-ten paths involve the moving parts of the turbine; these processes are dominantly materials (metals).

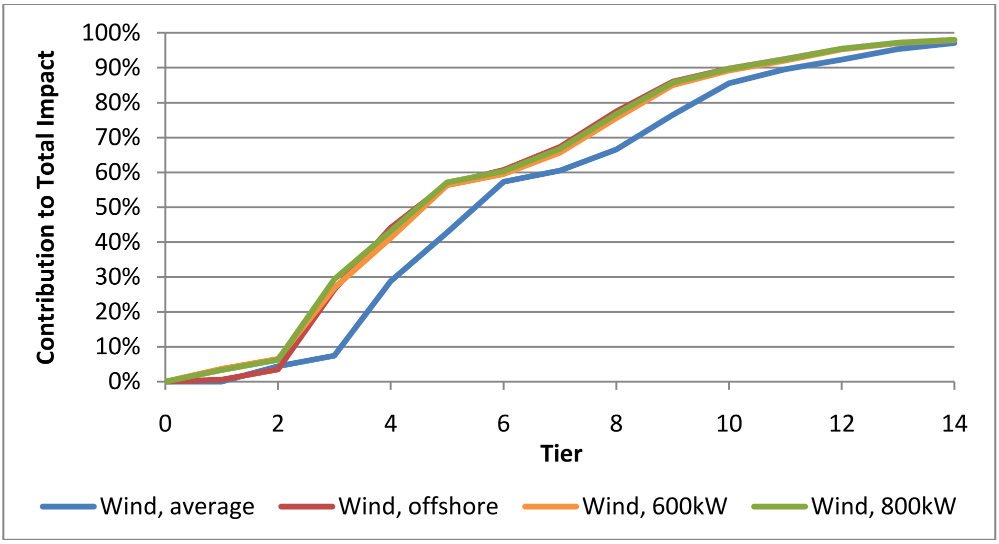

Figure 4.20: Cumulative contribution to total impact of wind energy technologies as a function of tier number.

Table 4.8: Structural path analysis results for wind power, 600 kW

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence(Wind, 600 kW→)
1	3	14.87	wind power plant 600kW, moving parts → glass fibre reinforced plastic, polyamide, injection moulding, at plant → nylon 66, glass-filled, at plant
2	1	3.34	wind power plant 600kW, fixed parts
3	5	2.46	wind power plant 600kW, moving parts → chromium steel 18/8, at plant → steel, converter, chromium steel 18/8, at plant → ferronickel, 25% Ni, at plant → hard coal, burned in industrial furnace 1-10MW
4	5	2.15	wind power plant 600kW, moving parts → copper, at regional storage → copper, primary, at refinery → copper concentrate, at beneficiation → disposal, sulfidic tailings, off-site
5	4	1.88	wind power plant 600kW, moving parts → chromium steel 18/8, at plant → steel, converter, chromium steel 18/8, at plant →

			ferrochromium, high-carbon, 68% Cr, at plant
6	4	1.56	wind power plant 600kW, fixed parts → concrete, normal, at plant → portland cement, strength class Z 42.5, at plant → clinker, at plant
7	4	1.50	wind power plant 600kW, fixed parts → steel, low-alloyed, at plant → steel, converter, low-alloyed, at plant → pig iron, at plant
8	5	1.45	wind power plant 600kW, moving parts → chromium steel 18/8, at plant → steel, electric, chromium steel 18/8, at plant → ferronickel, 25% Ni, at plant → hard coal, burned in industrial furnace 1-10MW
9	3	1.32	wind power plant 600kW, moving parts → copper, at regional storage → copper, primary, at refinery
10	4	1.26	wind power plant 600kW, moving parts → chromium steel 18/8, at plant → steel, converter, chromium steel 18/8, at plant → ferronickel, 25% Ni, at plant

Hydropower

In hydropower technologies, it is evident that the reservoir and run-of-river processes are quite similar (Figure 4.21). It should be noted, however, that reservoir hydropower has an impact in the zeroeth tier, while the run-of-river does not.

The pumped reservoir hydropower facility has a fairly different profile than the other technologies in hydropower. Examining the SPA table (Table 4.9), it is obvious that all of the paths for the top ten contributions to the process are results of fossil fuel combustion, extraction and disposal. This confirms the earlier speculation that the bulk, if not all, of the discrepancy between pumped reservoir hydropower and the other hydropower technologies investigated is assignable to fossil fuels. It is also interesting to note that all ten of the processes with highest contribution to impact are far into the background of the process, well after the first few tiers.

From the results of the SPA (Table 4.10Table 4.9), we can see that this impact in the zeroeth tier is due to the second-ranked path, which is the production of electricity at a pumped reservoir hydro plant. Significant impact in the reservoir hydropower technology does not occur until the fifth tier, which appears to be due to the production of clinker for the structural cement. Several of the top ten ranked paths in the pumped hydropower process involve the disposal phase. It is interesting to note that the ninth-ranked path contributes *negatively* to the total impact. It is difficult to assess what the cause of this negative value might be due to recycling of materials, and representing the avoided impact.

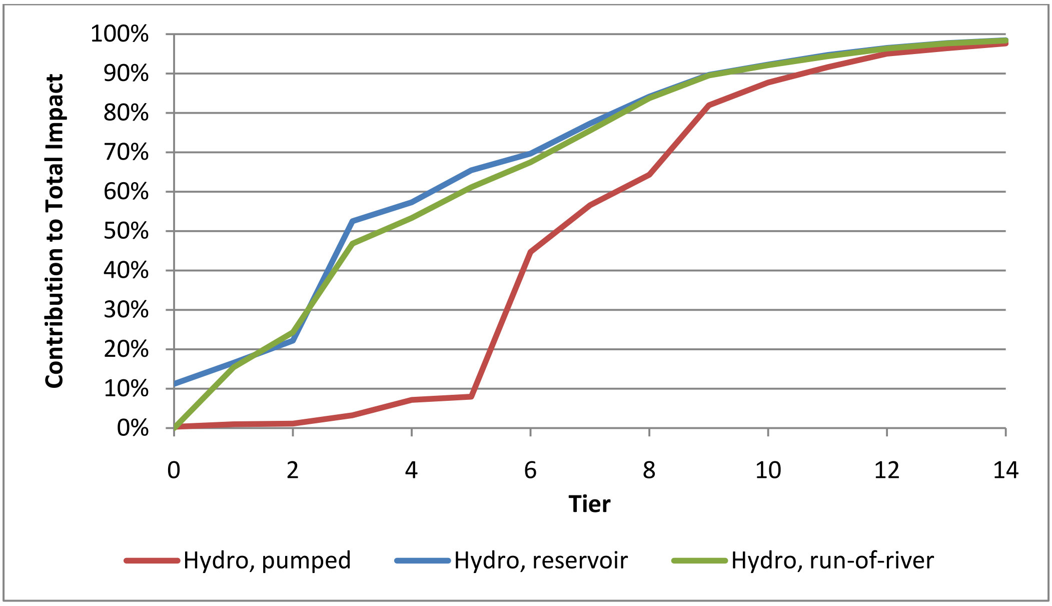

Figure 4.21: Cumulative contribution to total impact of hydropower technologies as a function of tier number

Table 4.9: Structural path analysis results for pumped reservoir hydropower process

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence(Hydro, pumped→)
1	6	5.10	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix DE→electricity, lignite, at power plant→lignite, burned in power plant
2	6	3.62	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix DE→electricity, hard coal, at power plant→hard coal, burned in power plant
3	7	2.86	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix DE→electricity, lignite, at power plant→lignite, burned in power plant→lignite, at mine
4	6	2.66	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix PL→electricity, hard coal, at power plant→hard coal, burned in power plant
5	6	2.41	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix ES→electricity, hard coal, at power plant→hard coal, burned in power plant
6	8	2.14	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix DE→electricity, lignite, at power plant→lignite, burned in power plant→lignite, at mine→disposal, spoil from lignite mining, in surface landfill
7	9	2.10	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix DE→electricity, hard coal, at power plant→hard coal, burned in power plant→hard coal supply mix→hard coal, at regional storage→
8	6	2.00	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix

			IT→electricity, natural gas, at power plant→natural gas, burned in power plant
9	6	1.89	electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix PL→electricity, lignite, at power plant→lignite, burned in power plant
10	9	1.82	electricity, hydropower, at pumped storage power plant→electricity, high voltage, at grid→electricity mix→electricity, production mix UCTE→electricity, production mix PL→electricity, hard coal, at power plant→hard coal, burned in power plant→hard coal supply mix→hard coal, at regional storage

Table 4.10: Structural path analysis results for reservoir hydropower process

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence (Hydro, reservoir→)
1	3	26.42	reservoir hydropower plant → portland cement, strength class Z 42.5, at plant → clinker, at plant
2	0	11.16	
3	1	5.20	reservoir hydropower plant
4	2	3.05	reservoir hydropower plant → disposal, building, reinforced concrete, to final disposal
5	3	2.31	reservoir hydropower plant → disposal, building, reinforced concrete, to final disposal → diesel, burned in building machine
6	5	2.13	reservoir hydropower plant → portland cement, strength class Z 42.5, at plant → clinker, at plant → hard coal, at regional storage → hard coal, at mine
7	2	2.11	reservoir hydropower plant → diesel, burned in building machine
8	4	1.38	reservoir hydropower plant → steel, low-alloyed, at plant → steel, converter, low-alloyed, at plant → pig iron, at plant
9	4	-1.10	reservoir hydropower plant → disposal, building, reinforced concrete, to final disposal → disposal, inert waste, 5% water, to inert material landfill → process-specific burdens, inert material landfill

10	7	1.05	reservoir hydropower plant → portland cement, strength class Z 42.5, at plant → clinker, at plant → heavy fuel oil, at regional storage → heavy fuel oil, at refinery → crude oil, production RaF, at long distance transport → crude oil, at production onshore

Solar Photovoltaic

The impact of the solar photovoltaic technologies shows a curve gradually increasing further towards the background (Figure 4.22), similar to the wind technology. It is interesting to note that both the multi-Si and the single-Si reach only approximately 90% of total emissions, even at the 14th tier.

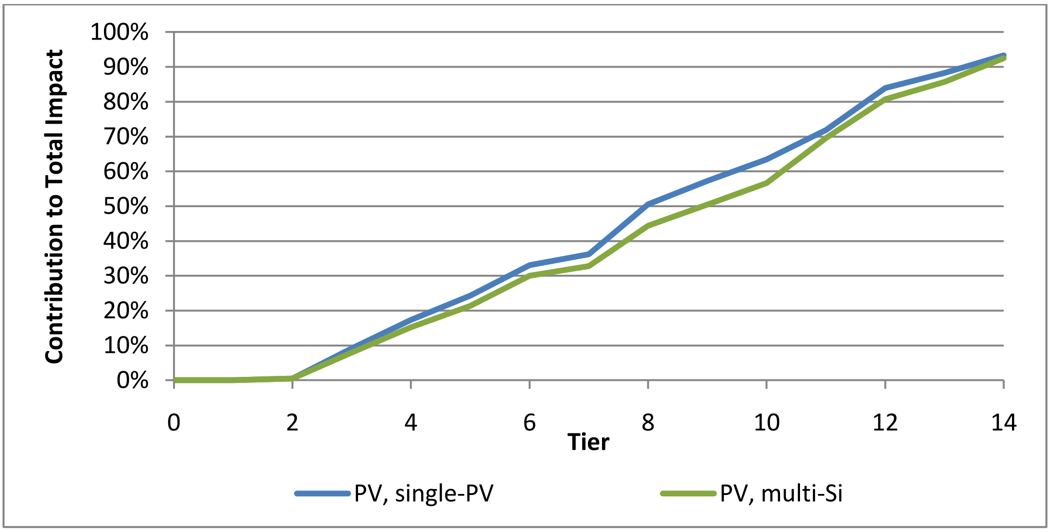

Figure 4.22: Cumulative contribution to total impact of solar photovoltaic technologies as a function of tier number

Upon examining the results of the SPA (Table 4.11), one can observe two things. The first is that the path length of the top 10 ranked paths varies quite a bit, and the other is that there are no single processes which contribute significantly more than the others. The top ranked path only has a contribution about 1% greater than the second ranked path. It is these trends which explain the flat nature of the cumulative impact chart. The most significant path ends at the production of electricity for the production of solar grade silicon. Other important paths include those for the production of the photovoltaic cell itself, polyethylene and the smelting of the aluminium for the frame.

Table 4.11: Structural path analysis results for photovoltaic, multi-SI process

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence (PV, multi-Si→)
1	8	4.44	3kWp flat roof installation, multi-Si, on roof → photovoltaic panel, multi-Si, at plant → photovoltaic cell, multi-Si, at plant → multi-Si wafer, at plant → silicon, multi-Si, casted, at plant → silicon, production mix, photovoltaics, at plant → silicon, solar grade, modified Siemens process, at plant → electricity, at cogen 1MWe lean burn, allocation exergy
2	3	3.38	3kWp flat roof installation, multi-Si, on roof → photovoltaic panel, multi-Si, at plant → photovoltaic cell, multi-Si, at plant
3	8	2.22	3kWp flat roof installation, multi-Si, on roof → photovoltaic panel, multi-Si, at plant → photovoltaic cell, multi-Si, at plant → multi-Si wafer, at plant → silicon, multi-Si, casted, at plant → silicon, production mix, photovoltaics, at plant → silicon, electronic grade, at plant → electricity, at cogen 1MWe lean burn, allocation exergy
4	3	2.08	3kWp flat roof installation, multi-Si, on roof → flat roof construction, on roof → polyethylene, HDPE, granulate, at plant
5	5	1.75	3kWp flat roof installation, multi-Si, on roof → flat roof construction, on roof → aluminium, production mix, wrought alloy, at plant → aluminium, primary, at plant → aluminium, primary, liquid, at plant
6	4	1.66	3kWp flat roof installation, multi-Si, on roof → photovoltaic panel, multi-Si, at plant → solar glass, low-iron, at regional storage → flat glass, uncoated, at plant
7	12	1.36	3kWp flat roof installation, multi-Si, on roof → photovoltaic panel, multi-Si, at plant → photovoltaic cell, multi-Si, at plant → multi-Si wafer, at plant → silicon, multi-Si, casted, at plant → silicon, production mix, photovoltaics, at plant → silicon, solar grade, modified Siemens process, at plant → electricity, at cogen 1MWe lean burn, allocation exergy → natural gas, high pressure,

			at consumer → natural gas, at long-distance pipeline → natural gas, production RU, at long-distance pipeline → natural gas, at production onshore
8	6	1.28	3kWp flat roof installation, multi-Si, on roof → electric installation, photovoltaic plant, at plant → copper, at regional storage → copper, primary, at refinery → copper concentrate, at beneficiation → disposal, sulfidic tailings, off-site
9	6	1.15	3kWp flat roof installation, multi-Si, on roof → inverter, 2500W, at plant → copper, at regional storage → copper, primary, at refinery → copper concentrate, at beneficiation → disposal, sulfidic tailings, off-site
10	4	1.06	3kWp flat roof installation, multi-Si, on roof → flat roof construction, on roof → disposal, building, polyethylene/polypropylene products, to final disposal → disposal, polyethylene, 0.4% water, to municipal incineration

Non-Renewable Energies

The cumulative impact curves for natural gas and coal are remarkably different from most of the renewable energy curves (Figure 4.23). Both curves show two distinct, sharp jumps.

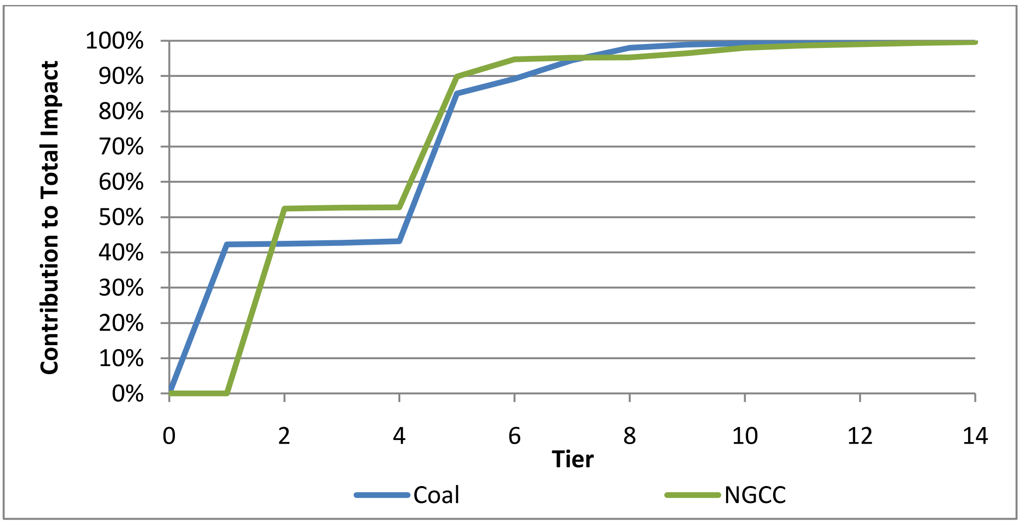

Figure 4.23: Cumulative contribution to total impact of fossil fuel technologies as a function of tier number

The process causing the first 'jump' in the natural gas curve is the burning of natural gas, contributing approximately 42% of the total impacts. The second jump, occurring in tier 5, is not associated with a single process, but several. All of these processes are the production of natural gas in other countries, both onshore and offshore (Table 4.12).

The results for coal show a similar path as for natural gas. The first jump is due to the combustion of coal at the power plant (22% contribution). The coal is sourced from several different regions; the other jump is due to several coal mining processes, again, from different countries. Thus, the most significant impacts occurring in the coal process is attributed to the combustion of the coal itself, and the mining of the coal.

Given the similarity of the results for both natural gas and coal, one can presume that most fossil fuels might follow the same pattern of experiencing sudden leaps in impact contribution in the combustion of the fuel and in the production or extraction of the fuel. Further fossil fuel processes should be analyzed to confirm this hypothesis.

Table 4.12: Structural path analysis results for natural gas combined cycle process

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence (NGCC →)
1	1	42.22	natural gas, burned in combined cycle plant, best technology
2	5	14.83	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production RU, at long-distance pipeline → natural gas, at production onshore
3	5	7.26	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production NL, at long-distance pipeline → natural gas, at production onshore
4	5	7.16	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-

			distance pipeline → natural gas, production NO, at long-distance pipeline → natural gas, at production offshore
5	5	3.96	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production DZ, at long-distance pipeline → natural gas, at production onshore
6	5	2.88	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production NL, at long-distance pipeline → natural gas, at production offshore
7	8	2.87	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production DZ, at long-distance pipeline → natural gas, production DZ, at evaporation plant → natural gas, liquefied, at freight ship → natural gas, liquefied, at liquefaction plant → natural gas, at production onshore
8	6	2.35	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production RU, at long-distance pipeline → transport, natural gas, pipeline, long distance → natural gas, burned in gas turbine, for compressor station
9	7	2.31	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production RU, at long-distance pipeline → transport, natural gas, pipeline, long distance → natural gas, burned in gas turbine, for compressor station → natural gas, at production onshore
10	5	2.14	natural gas, burned in combined cycle plant, best technology → natural gas, high pressure, at consumer → natural gas, at long-distance pipeline → natural gas, production DE, at long-distance pipeline → natural gas, at production onshore

Table 4.13: Structural path analysis results for hard coal combustion process

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence (Coal →)
1	2	22.29	electricity, hard coal, at power plant → hard coal, burned in power plant
2	5	12.91	electricity, hard coal, at power plant → hard coal, burned in power plant → hard coal supply mix → hard coal, at regional storage → hard coal, at mine
3	2	11.28	electricity, hard coal, at power plant → hard coal, burned in power plant
4	2	4.99	electricity, hard coal, at power plant → hard coal, burned in power plant
5	2	4.47	electricity, hard coal, at power plant → hard coal, burned in power plant
6	2	3.63	electricity, hard coal, at power plant → hard coal, burned in power plant
7	5	2.92	electricity, hard coal, at power plant → hard coal, burned in power plant → hard coal supply mix → hard coal, at regional storage → hard coal, at mine
8	2	2.61	electricity, hard coal, at power plant → hard coal, burned in power plant
9	2	2.27	electricity, hard coal, at power plant → hard coal, burned in power plant
10	5	1.75	electricity, hard coal, at power plant → hard coal, burned in power plant → hard coal supply mix → hard coal, at regional storage → hard coal, at mine

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5. Discussion

5.1 Data Quality

The ***A***, ***S*** and ***C*** matrices used had not been checked for errors or otherwise passed through quality control. There is thus a remote possibility that there may be errors present in the data used for this study. Since the main purpose of script written for this study is to allow the simultaneous analysis of multiple processes and to simplify the export of the results to an Excel file, the possibility exists to cross-check some of the results using available LCA software such as SimaPro.

However, the ecoinvent 2.2 database was not yet offered on the SimaPro subscription at the time when the analysis was conducted. Instead, some of the impacts obtained in this analysis were compared to the ecoinvent 2.0 database processes available. For the most part, impacts did not differ by more than 10%. While this would seem to indicate that there are no significant issues with the data used in the analysis, it recommended nonetheless that the data used be checked, and the analysis re-conducted should any changes be made to the data.

5.2 Methodology

The results from this study may also be affected by inconsistencies found amongst the different technologies selected. Larger facilities are compared to facilities with less capacity. Although some of this might be attributed to the nature of the energy source – it is much easier to build a 15 GWh hydropower dam than a 15 GWh solar photovoltaic farm – some of these discrepancies are merely a result of the facilities sampled when the ecoinvent database was assembled. The larger facilities thus have a bias towards lower impact due to economies of scale.

It should be noted that the results of this study are merely a static snapshot of the technologies examined; the ecoinvent inventory processes reflect the technology available at the time the inventory analysis was performed. Consequently, the processes examined here use the technology that may be several years old, although the database is continuously reviewed and some processes are updated. Renewable energy technology is constantly improving in material and energy use and in efficiency. Thus, it can be speculated that in the near future, these technologies would experience significant improvements in performance and thus have a reduced environmental impact than presented in this study. To keep abreast of new renewable energy technologies, this study should be re-performed when significant advances are made, or every few years to assess the improvements being made in the sector.

Upon examining the calculation results, it was evident on several processes that there were negative values in the output vector, $\boldsymbol{x}$. The cause for this may be due to allocation methods, including credit being awarded for avoided impacts. Though in the negative values observed appeared to be insignificantly small in magnitude, there remains the question of how to deal with them in the calculations. As SimaPro does not display negative numbers for output on the results screen, it is possible that the software sets these values to 0 before continuing with calculations. This would then affect all subsequent calculations, which may be the cause of the slight discrepancy observed between the SimaPro calculation results and those produced by the Matlab script written in this study. Given more time, it would have been interesting to investigate this issue further.

5.3 Assessment of Results

The qualitative results obtained from this study varied slightly from that of Jacobsen (2009), although the results confirmed the results observed in Jungbluth, Bauer et al. (2005). Of the processes examined in both Jacobsen and in this study, wind had the least impact, followed by solar photovoltaic, hydropower, and lastly, biofuels. In this study, the rank is hydropower (excluding pumped reservoir), wind, solar photovoltaic and biofuels. In Jacobsen's work, however, he calculates a ranking system and the study compared performance in powering fuel cell- and battery-driven vehicles.

While the aggregation of ecoinvent processes into coarse sectors of materials provided some insightful results, it would have been of benefit to re-analyze using a further refined aggregation scheme. as an example, the waste category proved to be one of the most significant material categories in all processes examined, and yet, it was difficult to determine whether the waste fell into the hazardous waste sub-category, or material recovery and recycling. The former has severely detrimental environmental and health effects, inferring a large impact, while the other has a relatively minimal impact. As another example, concrete and cement were combined together with the mining of raw materials. Because these two materials are so widely used in construction, it led to misleadingly large results in the mining/minerals category. It would have been beneficial to have separated them into standalone category.

5.4 Application of Results

In recent years, renewable energies, which use energy sources that do not suffer from a limited, finite supply, have been hailed as the saviour for humanity's global warming problems. While it is true that these are, in essence, unlimited supplies of energy, there are also negative aspects which are often overlooked by the average citizen. One of these aspects is land use and energy density. Currently, the efficiency of the technologies used to harness and convert renewable energy into electricity remains sadly limited. The energy density of these technologies is thus usually quite low (Ausubel 2007), resulting in renewable energy plants that often occupy large tracts of land. This land may have been prime land which has been cleared or destroyed and may have otherwise been used for production of agriculture. Thus, although the energy itself may be nearly free, the capability of humans to capture it has high land use and transformation impacts.

Another factor that should be considered is the volatile nature of renewable energy sources. These sources are diurnal and seasonal, and vulnerable to changes in weather patterns. Until an effective method of storing electrical energy is developed, those planning for renewable energy power plants must be aware of these changes and implement measures to make up electricity supply shortcomings. Geographical appropriateness must also be considered when planning a renewable energy facility; not all locations are universally appropriate for any given renewable energy. How productive would a solar panel be in the far north, when the highest demand for electricity would occur at the same time as when there is no sun to be seen for months?

These aforementioned criticisms of renewable energy should not, however, discourage the greater adoption of renewable energy in the global energy mix. With careful planning and further technological developments, it is possible maximize the potential of these energy sources without having their weaknesses cause disasters. Instead, it should be taken upon as a challenge to develop a renewable energy scheme that involves load-matching for diurnal and perhaps seasonal variations in supply.

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6. Future Work

While this work provides a general comparison of environmental performance of common renewable and non-renewable sources of electricity, further work should be performed to increase understanding of the nature of the differences.

This study uses the total, single-score ReCiPe endpoint indicator as a general measure of overall environmental performance. However, it would provide some insight into the results to examine the endpoints using their native units (DALY, $, species.yr). Unfortunately, these endpoint indicators were not available in the dataset used for this study.

Due to the inexact nature of environmental modelling and relatively poor understanding of the fate chemicals in the environment, the results presented here may contain bias inherent in the ReCiPe assessment method. This study should be replicated using other methods such as EcoIndicator 99 or CML 2000 to examine the sensitivity of the results to the characterization method used.

The future of an energy technology is largely dictated by the politicians in power. The bottom line relies not only on environmental performance, but also on economic performance. It would be advisable to perform a joint environmental and economic analysis to obtain a whole-picture view. Various scenarios may be examined, with different carbon tax levels and future technologies being adopted. It would be of interest to determine when an energy supply based solely on renewable sources becomes economically sound as well as environmentally sound.

It would be a daunting, yet rewarding task to carry on the work presented in this thesis with a more comprehensive selection of processes. Although this study covers the most common sources of energy mentioned by Lenzen (2010) and the IEA (2009), it would be of interest to consider other sources, such oil, nuclear, tidal and geothermal energies.

The aggregation of sub-processes in terms of materials uncovered much about distribution of impacts in the energy systems analyzed. However, it would also be of interest to analyze the processes in terms of life-cycle stages such as manufacture and assembly, operation and maintenance, and decommissioning. It would valuable for and of interest to policy makers and energy companies to be aware at what stage or stages the majority of impacts occur so that further research and development can be targeted to those areas.

It would also be an interesting exercise in optimization to ‘build’ the ideal electricity mix. One could assume all energy sources were equally available, or perform a case study for a specific geographical region, thereby setting some limitations, then determine what proportions of each energy source and technology would work together with their shortcomings as mentioned in §5.4, and have the lowest impact possible. This outcome of work such as this could be used in the future by policy makers who wish to reach certain energy-related goals as the EU’s 21% renewable-by-2010 Directive.

7. Conclusion

Given the analyses performed in this study, it can be concluded that in general, renewable energy sources producing electricity have less of an impact on human health, ecosystem damage and resource depletion than the fossil fuels natural gas and hard coal.

Of the renewable energy technologies studied, the wind power and hydropower sources consistently had the least impact. The run-of-river hydropower plant and on-land wind turbines had particularly low impacts in comparison to the other processes. The coal power had the poorest performance of all processes examined in the majority of the categories, and the most impact overall. While the natural gas combined cycle facility generally had a greater impact than renewable, its performance still exceeded that of the coal power, and in some categories, was competitive with renewable energy sources.

With the exception of bioenergy and pumped reservoir hydropower, the various technologies available to produce electrical energy from renewable resources did not show significant differences. Indeed, bioenergy seemed to be the most unpredictable source of renewable energy, and was often not significantly superior to fossil fuels.

It is recommended that this study be performed regularly in the future using more recent technologies in order to maintain an awareness of the progress of technologies in the future. A similar analysis should also be conducted on other renewable and non-renewable technologies for comparison. Despite what the critics of renewable energy may say, they are still far better in most realms than the sources of energy currently being used.

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Appendices

Matlab Code

```
% main.m
% Christine Hung, June 2010
% Data preprocessing should be performed before running this script
(prep.m)

load thesis_matrices_prepped.mat

%User modifiable variables
ind=[3393,3394,3395,3396,3400,3403,301,307,418,3153,2564,2565,1529,1547,
1552,2143,1406];
% ind=[3393,3394,3395,3396]; %Wind
% ind=[3400,3403,301,307,418,3153]; %Bioenergy
% ind=[2564,2565]; %PV
% ind=[1529,1547,1552]; %Hydroelectricity
% ind=[2143,1406]; %NGCC and coal

%Set up global variables
I=sparse(eye(size(A,1)));
num_tiers=15; % for Taylor series. Default to 6 tiers (from tier 0 to 5)
tolerance=0.005; % tolerance for SPA in %

% Set up constants and formatting for Taylor Series Expansion
CS=C_ReCiPe_endpt_H*S;
CSm=C_ReCiPe_midpt_H*S;

d_norm_tot=zeros(19,num_tiers);

letter=char(double('E')+num_tiers+1);

plot_tay_head=endpt_head(7,1);
plot_tay_head=[plot_tay_head;endpt_head(17,1)];
plot_tay_head=[plot_tay_head;endpt_head(20,1)];
plot_tay_head=[plot_tay_head;midpt_head(1:15,1)];
plot_tay_head=[plot_tay_head;endpt_head(21,1)];

for n=1:length(ind),
%Generate unique file names for each process
    temp=char(PRO_head(ind(n),1));
    fileName=strrep(temp,' ', '_');
    fileName=strrep(fileName,'/','_');
    fileName=strrep(fileName,' ', '_');
    fileName=strrep(fileName,'.', ',');
    fileName_mat=strcat(fileName,'.mat');
    fileName_xls=strcat(fileName,'.xls');

    fprintf(1,'Beginning calculation of %s',fileName);
    tic;
    %% Calculate total output vector
    y=zeros(size(A,1),1);
    y(ind(n),1)=2.78E-7*10^18; %1 EJ = 2.78x10^11 kWh
```

```
y=sparse(y);

% Find total output vector
x=(I-A)\y;
%% Basic Contribution Analysis
% Find emissions and impacts due to final demand
e=S*x;
E=S*diag(x);
E_agg=E*EI2Agg;
E_mat=E*mat_agg';

%ReCiPe midpoint and endpoint calculations
% Hierarchist
d_h=C_ReCiPe_midpt_H*e;
D_h=C_ReCiPe_midpt_H*E;
D_h_agg=C_ReCiPe_midpt_H*E_agg;
D_h_mat=C_ReCiPe_midpt_H*E_mat;

endpt_h=C_ReCiPe_endpt_H*e;
endpt_h_agg=C_ReCiPe_endpt_H*E_agg;

% Egalitarian
d_e=C_ReCiPe_midpt_E*e;
D_e=C_ReCiPe_midpt_E*E;
D_e_agg=C_ReCiPe_midpt_E*E_agg;

endpt_e=C_ReCiPe_endpt_E*e;
endpt_E_SPA=C_ReCiPe_endpt_E*E;
endpt_e_agg=C_ReCiPe_endpt_E*E_agg;

% Individualist
d_i=C_ReCiPe_midpt_I*e;
D_i=C_ReCiPe_midpt_I*E;
D_i_agg=C_ReCiPe_midpt_I*E_agg;

endpt_i=C_ReCiPe_endpt_I*e;
endpt_i_agg=C_ReCiPe_endpt_I*E_agg;

D_str=C*diag(e);

%% Material Flow Analysis
% Calculate material flow matrix

Zi = A*x; %total material flow due to output, x
Zi_agg=mat_agg*Zi;

%% Taylor Expansion
% Tier analysis using geometric series expansion
% Performed on hierarchical perspective, endpoint and midpoint

tier=zeros(1,num_tiers);
%total impact for normalized values
d=endpt_h;
dm=d_h;
```

```
    A_acc=I;
    x_tay=zeros(size(A,1),num_tiers);
    d_tay=zeros(size(CS,1),num_tiers);
    d_acc=zeros(size(CS,1),num_tiers);
    d_norm=zeros(size(CS,1),num_tiers); %normalized taylor impacts (% of
total impact)
    temp_A=A; %placeholder for A matrix to reduce calculation intensity

    %Taylor Expansion variables for midpoint indicators
    d_taym=zeros(size(CSm,1),num_tiers);
    d_accm=zeros(size(CSm,1),num_tiers);
    d_normm=zeros(size(CSm,1),num_tiers);
    for j=1:num_tiers,
        tier(1,j)=j-1;
        if j==1, %for the 0th tier (foreground)
            x_tay(:,j)=I*y;
            d_tay(:,j)=CS*y;
            d_acc(:,j)=d_tay(:,j);

            d_taym(:,j)=CSm*y;
            d_accm(:,j)=d_taym(:,j);

        else
            x_tay(:,j)=A*x_tay(:,j-1);
            d_tay(:,j)=CS*x_tay(:,j);
            A_acc=A_acc+temp_A;
            temp_A=temp_A*A;
            d_acc(:,j)=CS*A_acc*y;

            d_taym(:,j)=CSm*x_tay(:,j);
            d_accm(:,j)=CSm*A_acc*y;
        end;
            d_norm(:,j)=d_acc(:,j)./d;
            d_normm(:,j)=d_accm(:,j)./dm;
    end;
    % Separate total endpoints and land use midpoint indicators for plot
    d_norm_tot(1,:)=d_norm(7,:);
    d_norm_tot(2,:)=d_norm(17,:);
    d_norm_tot(3,:)=d_norm(20,:);
    d_norm_tot(4:18,:)=d_normm(1:15,:);
    d_norm_tot(19,:)=d_norm(21,:);

    clear temp_A;
    clear A_acc;
    clear i;
    clear j;
    clear k;
    clear p;
    clear n;
    clear temp;

 %% Print results to Excel file

    xlswrite(fileName_xls,'y','x_y','C1');
    xlswrite(fileName_xls,PRO_head,'x_y','A2');
```

```
    xlswrite(fileName_xls,y,'x_y','C2');

    xlswrite(fileName_xls,'x','x_y','D1');
    xlswrite(fileName_xls,x,'x_y','D2');

    % Write emissions inventory
    xlswrite(fileName_xls,'e','emissions inventory');
    xlswrite(fileName_xls,STR_head(:,1:2),'emissions inventory','A3');
    xlswrite(fileName_xls,e,'emissions inventory','C3');

    xlswrite(fileName_xls,{'Aggregated Process Emissions'},'emissions
inventory', 'D1');
    xlswrite(fileName_xls,agg_head,'emissions inventory','E2');
    xlswrite(fileName_xls,E_agg,'emissions inventory','E3');

    % Write aggregated material flow
    xlswrite(fileName_xls,{'Aggregated Material Flows'},'material flow');
    xlswrite(fileName_xls,agg_head','material flow','A3');
    xlswrite(fileName_xls,Zi_agg,'material flow','B3');

    %Write impacts
    xlswrite(fileName_xls,{'Midpoint Impacts'},'impacts');
    xlswrite(fileName_xls,midpt_head,'impacts','A2');
    xlswrite(fileName_xls,{'Hierarchical'},'impacts','D1');
    xlswrite(fileName_xls,d_e,'impacts','E2');
    xlswrite(fileName_xls,{'Egalitarian'},'impacts','E1');
    xlswrite(fileName_xls,d_h,'impacts','D2');
    xlswrite(fileName_xls,{'Individualist'},'impacts','F1');
    xlswrite(fileName_xls,d_i,'impacts','F2');

    xlswrite(fileName_xls,{'Endpoint Impacts'},'impacts','A21');
    xlswrite(fileName_xls,endpt_head,'impacts','A22');
    xlswrite(fileName_xls,{'Hierarchical'},'impacts','D21');
    xlswrite(fileName_xls,endpt_h,'impacts','D22');
    xlswrite(fileName_xls,{'Egalitarian'},'impacts','E21');
    xlswrite(fileName_xls,endpt_e,'impacts','E22');
    xlswrite(fileName_xls,{'Individualist'},'impacts','F21');
    xlswrite(fileName_xls,endpt_i,'impacts','F22');

    %Write aggregated process-specific midpoint impacts
    xlswrite(fileName_xls,{'D_aggregated - hierarchical'},'D_mat','A1');
    xlswrite(fileName_xls,mat_head,'D_mat','D2');
    xlswrite(fileName_xls,midpt_head,'D_mat','A3');
    xlswrite(fileName_xls,D_h_mat,'D_mat','D3');


    xlswrite(fileName_xls,{'D_aggregated - hierarchical'},'D_agg','A1');
    xlswrite(fileName_xls,agg_head,'D_agg','D2');
    xlswrite(fileName_xls,midpt_head,'D_agg','A3');
    xlswrite(fileName_xls,D_h_agg,'D_agg','D3');

    xlswrite(fileName_xls,{'D_aggregated - egalitarian'},'D_agg','A22');
    xlswrite(fileName_xls,agg_head,'D_agg','D23');
    xlswrite(fileName_xls,midpt_head,'D_agg','A24');
    xlswrite(fileName_xls,D_e_agg,'D_agg','D24');
```

```
    xlswrite(fileName_xls,{'D_aggregated - individualist'},'D_agg','A43');
    xlswrite(fileName_xls,agg_head,'D_agg','D44');
    xlswrite(fileName_xls,midpt_head,'D_agg','A45');
    xlswrite(fileName_xls,D_i_agg,'D_agg','D45');

    %Write aggregated endpoint results
    xlswrite(fileName_xls,{'Endpoint aggregated -
hierarchical'},'end_agg','A1');
    xlswrite(fileName_xls,agg_head,'end_agg','D2');
    xlswrite(fileName_xls,endpt_head,'end_agg','A3');
    xlswrite(fileName_xls,endpt_h_agg,'end_agg','D3');

    xlswrite(fileName_xls,{'Endpoint aggregated -
egalitarian'},'end_agg','A25');
    xlswrite(fileName_xls,agg_head,'end_agg','D26');
    xlswrite(fileName_xls,endpt_head,'end_agg','A27');
    xlswrite(fileName_xls,endpt_e_agg,'end_agg','D27');

    xlswrite(fileName_xls,{'Endpoint aggregated -
individualist'},'end_agg','A49');
    xlswrite(fileName_xls,agg_head,'end_agg','D50');
    xlswrite(fileName_xls,endpt_head,'end_agg','A51');
    xlswrite(fileName_xls,endpt_i_agg,'end_agg','D51');

    % Write Taylor series expansion
    xlswrite(fileName_xls,{'Endpoint Impacts, Taylor Series Expansion
(Hierarchical)'},'Taylor');
    xlswrite(fileName_xls,{'Number of tiers:'},'Taylor','A2');
    xlswrite(fileName_xls,num_tiers,'Taylor','B2');

    xlswrite(fileName_xls,tier,'Taylor','D4');
    xlswrite(fileName_xls,endpt_head,'Taylor','A5');
    xlswrite(fileName_xls,d_tay,'Taylor','D5');

    p={'Cumulative impacts'};
    xlswrite(fileName_xls,p,'Taylor',strcat(letter,'3'));
    xlswrite(fileName_xls,tier,'Taylor',strcat(letter,'4'));
    xlswrite(fileName_xls,d_acc,'Taylor',strcat(letter,'5'));

    p={'Normalized impacts'}; % To have all indicators on same graph
    xlswrite(fileName_xls,p,'Taylor','A28');
    xlswrite(fileName_xls,tier,'Taylor','D28');
    xlswrite(fileName_xls,endpt_head,'Taylor','A29');
    xlswrite(fileName_xls,d_norm,'Taylor','D29');

    %% Concise data for plotting
    % Taylor Series Expansion data for plot
    p={'Total Normalized Impacts, Taylor Series'};
    xlswrite(fileName_xls,p,'Plot');
    xlswrite(fileName_xls,plot_tay_head,'Plot','A3');
    xlswrite(fileName_xls,tier,'Plot','B2');
    xlswrite(fileName_xls,d_norm_tot,'Plot','B3');

    xlswrite(fileName_xls,agg_head,'Plot','B25');
```

```
    xlswrite(fileName_xls,midpt_head(1:15,1),'Plot','A26');
    xlswrite(fileName_xls,D_h_agg(1:15,:),'Plot','B26');

    xlswrite(fileName_xls,midpt_head(1:15,1),'Plot','A43');
    xlswrite(fileName_xls,{'Hierarchical'},'Plot','B42');
    xlswrite(fileName_xls,d_h(1:15,1),'Plot','B43');
    xlswrite(fileName_xls,{'Egalitarian'},'Plot','C42');
    xlswrite(fileName_xls,d_e(1:15,1),'Plot','C43');
    xlswrite(fileName_xls,{'Individualist'},'Plot','D42');
    xlswrite(fileName_xls,d_i(1:15,1),'Plot','D43');
    xlswrite(fileName_xls,endpt_head,'Plot','A60');
    xlswrite(fileName_xls,{'Hierarchical'},'Plot','B59');
    xlswrite(fileName_xls,endpt_h,'Plot','B60');
    xlswrite(fileName_xls,{'Egalitarian'},'Plot','C59');
    xlswrite(fileName_xls,endpt_e,'Plot','C60');
    xlswrite(fileName_xls,{'Individualist'},'Plot','D59');
    xlswrite(fileName_xls,endpt_i,'Plot','D60');

    %% SPA
    F_spa=CS(21,:); %Use total hierarchical endpoint indicator for SPA
    spa=SPA2(F_spa,A,y,num_tiers,tolerance,fileName);
    %% Supplemental data
    xlswrite(fileName_xls,{'Midpoint Impacts, Taylor Series Expansion
(Hierarchical)'},'Taylor-mid');
    xlswrite(fileName_xls,{'Number of tiers:'},'Taylor-mid','A2');
    xlswrite(fileName_xls,num_tiers,'Taylor-mid','B2');

    xlswrite(fileName_xls,tier,'Taylor-mid','D4');
    xlswrite(fileName_xls,midpt_head,'Taylor-mid','A5');
    xlswrite(fileName_xls,d_taym,'Taylor-mid','D5');

    p={'Cumulative impacts'};
    xlswrite(fileName_xls,p,'Taylor-mid',strcat(letter,'3'));
    xlswrite(fileName_xls,tier,'Taylor-mid',strcat(letter,'4'));
    xlswrite(fileName_xls,d_accm,'Taylor-mid',strcat(letter,'5'));

    p={'Normalized impacts'}; % To have all indicators on same graph
    xlswrite(fileName_xls,p,'Taylor-mid','A25');
    xlswrite(fileName_xls,tier,'Taylor-mid','D25');
    xlswrite(fileName_xls,midpt_head,'Taylor-mid','A26');
    xlswrite(fileName_xls,d_normm,'Taylor-mid','D26');

    xlswrite(fileName_xls,{'D - hierarchical (translated)'},'D','A1');
    xlswrite(fileName_xls,PRO_head,'D','A4');
    xlswrite(fileName_xls,midpt_head','D','B1');
    xlswrite(fileName_xls,D_h','D','B4');

    xlswrite(fileName_xls,{'D - egalitarian (translated)'},'D','U1');
    xlswrite(fileName_xls,midpt_head','D','V1');
    xlswrite(fileName_xls,D_e','D','V4');

    xlswrite(fileName_xls,{'D - individualist (translated)'},'D','AP1');
    xlswrite(fileName_xls,midpt_head','D','AQ1');
    xlswrite(fileName_xls,D_i','D','AQ4');
```

```
save(fileName,'x*','y','Z*','e','E','d*','D*','endpt*','spa','num_tiers'
,'tolerance');
    toc;
end
%clean up temporary variables
clear CS;
clear CSm;
clear d*;
clear D*;
clear fileName*;
```

```
% prep.m
% Christine Hung, June 2010

% This script should be run prior to running main.m; it reads the
% aggregation matrices from the Excel file 'read.xls' and makes
adjustments
% to the interindustry matrix, A and the characterization matrices.

clear all;
load thesis_matrices.mat

EI2IO=sparse(xlsread('read_data.xls','EI2.2 to IO','D3:FA4089'));
IO2Agg=sparse(xlsread('read_data.xls','IO to Aggregated','B2:Q155'));

EI2Agg=EI2IO*IO2Agg;

mat_agg=xlsread('read_data.xls','material agg','T2:AI4088');
mat_agg=mat_agg';

% Adjust A matrix to remove -1s on diagonal
diagAdj=diag(ones(length(A),1));
A=A+diagAdj;

C_ReCiPe_endpt_I=C_ReCiPe_endpt_I';
C_ReCiPe_endpt_E=C_ReCiPe_endpt_E';
C_ReCiPe_endpt_H=C_ReCiPe_endpt_H';

C_ReCiPe_midpt_I=C_ReCiPe_midpt_I';
C_ReCiPe_midpt_E=C_ReCiPe_midpt_E';
C_ReCiPe_midpt_H=C_ReCiPe_midpt_H';
clear diagAdj;
save('thesis_matrices_prepped.mat')
```

```
function sorted_paths = SPA2(F, A, y, Tmax, TolPrc, varargin)
% SPA2    Structural path analysis.
%   Paths = SPA2(F, A, Y, TMax, TolPrc) carries out a structural path
%   analysis (SPA) for the system with N industrial sectors based on the
%   algorithm proposed by Peters and Hertwich (2006, ESR), where F is a
%   1-by-N vecotor of the environmental impact per unit output, A is an
%   N-by-N matrix of the inter-industry requirements, and Y is an N-by-1
%   vector of the final demand.  Every path up to the TMax-th tier is
%   explored if the sub-tree below it contributes as much as, or more
%   than, the (100*TolPrc)% of the total emission, which is given by
%   F*inv(eye(n)-A)*Y.
%   The p-th path represented as a sequence of industrial sectors is
%   stored in the vector of integers of type UINT16, Path(p).sequenc.
%   Its value is also stored in Path(p).value.
%
%   Paths = SPA2(F, A, Y, TMax, TolPrc, FileName) carries out the SPA
%   above while additionally saving the results to a MAT-file and writing
%   them to a TXT-file.  The names of the MAT- and TXT-files are,
%   respectively, given by
%       sprintf('%s_paths_%d.mat', FileName, TMax) and
%       sprintf('%s_print_%d.mat', FileName, TMax);
%   for example, they are 'MySPA_paths_3.mat' and'MySPA_print_3.mat' if
%   FileName=='MySPA' and TMax==3.
%
%   Paths = SPA2(F, A, Y, TMax, TolPrc, FileName, FTotal) carries out the
%   SPA above while allowing a user to save the computation time by
%   giving the vector FTotal=F/(eye(n)-A).  This optional input argument
%   is effective when the user has already obtained the vector FTotal in
%   previous analyses.  If the user would not like to save or write the
%   results to files, she/he can set FileName equal to the null string,
%   i.e., FileName==''.
%
%   For wizards and MATLAB experts:
%   SPA2 recognizes the eighth optional input argument, say M.  A 1-by-M
%   structure array is defined before extracting paths in order to
%   prevent iterative memory assignments.

% Yasushi Kondo, Oct 2009
% Modification of Glen Peters' codes developed in Feb 2005.

% Managing optional input arguments
% Number of industrial sectors
N = length(y);

if (nargin < 8)
  % Tentative number of paths to declare a variable in which the results
  % is stored.
  MaxNumPaths = 20000;
else
  MaxNumPaths = varargin{3};
end

if (nargin < 7)
  Ftotal = F / (eye(N) - A);
else
```

```
  Ftotal = varargin{2};
end

if (nargin < 6)
  FileName = '';
else
  FileName = varargin{1};
end

%% Extracting paths along a tree
% Calculate the total emissions and tolerance
TotalEmissions = Ftotal * y;
Tol = TolPrc / 100 * TotalEmissions;

% Extract paths
fprintf(1, 'Extracting paths along a tree...   ')
tic
paths = ExtractPaths(F, A, y, Ftotal, Tmax, Tol, MaxNumPaths);
fprintf(1, '\n    ');
toc

% Sort the extracted paths in a descending order of their values
fprintf(1, 'Sorting paths...   ')
tic
sorted_paths = SortPaths(paths);
fprintf(1, '\n    ');
toc

% Saving the results to files
FileName_xls=strcat(FileName,'.xls');
fprintf(1, 'Writing sorted paths to Excel file %s...   ', FileName)
tic
PrintPaths(sorted_paths, Tmax, TolPrc, TotalEmissions, FileName_xls);
fprintf(1, '\n    ');
toc
end
```

```
function paths = ExtractPaths(F, A, y, Ftotal, Tmax, Tol, MaxNumPaths)
% ExtractPaths    A subroutine called by SPA2
%     Extracting paths along a tree.

% Yasushi Kondo, Oct 2009

% Declaration of an array for storing paths
paths(1:MaxNumPaths)      =      struct('value',      NaN,      'sequence',
zeros(1,Tmax,'uint16'));

[paths, cnt] = ExtractPaths_rc(paths, ...
  0, ...            % cnt
  uint16([]), ... % sequence
  NaN, ...          % Val_wo_F
  0, ...            % T
  F, A, y, Ftotal, Tmax, Tol);

paths = paths(~isnan([paths.value]));
```

```
function [paths, cnt] = ExtractPaths_rc(paths, cnt, sequence, Val_wo_F,
T, F, A, y, Ftotal, Tmax, Tol)
% ExtractPaths_rc    A subroutine recursively called by ExtractPaths
%      Extracting paths along a tree.

% Yasushi Kondo, Oct 2009

N =length(y);

if (T > 0)
  cnt = cnt + 1;
  paths(cnt).sequence = sequence;
  paths(cnt).value = full(F(sequence(end)) * Val_wo_F);
end

if (T < Tmax)
  if (T == 0)
    NextVal_wo_F = y;
  else
    NextVal_wo_F = A(:,sequence(end)) * Val_wo_F;
  end

  NextSubtreeVal = Ftotal' .* NextVal_wo_F;
  ToBeSearched = find(abs(NextSubtreeVal) >= Tol);
  for ii = ToBeSearched';
    [paths, cnt] = ExtractPaths_rc(paths, cnt, [sequence, uint16(ii)],
      NextVal_wo_F(ii), T+1, F, A, y, Ftotal, Tmax, Tol);
  end
end
```

```
function sorted = SortPaths(paths)
% Sort the paths in terms of value

[SortedValeus, SortedIndices] = sort(abs([paths.value]), 2, 'descend');
sorted = paths(SortedIndices);
```

```
function PrintPaths(paths, Tmax, TolPrc, TotalEmissions, FileName)
% PrintPaths
% Christine Hung, June 2010, modified from Yasushi Kondo, Oct 2009
% Modification of Glen Peters' codes developed in Feb 2005.
% A subroutine called by SPA2
% Write the extracted paths to an Excel file

NumPaths = length(paths);

xlswrite(FileName,{'Number of paths'},'SPA');
xlswrite(FileName,NumPaths,'SPA','B1');
xlswrite(FileName,{'Highest tier explored'},'SPA','A2');
xlswrite(FileName,Tmax,'SPA','B2');
xlswrite(FileName,{'Tolerance in percentage'},'SPA','A3');
xlswrite(FileName,TolPrc,'SPA','B3');
xlswrite(FileName,{'Direct Emissions'},'SPA','A4');
xlswrite(FileName,TotalEmissions,'SPA','B4');

xlswrite(FileName,{'Path Rank'},'SPA','A10');
xlswrite(FileName,{'Path Length'},'SPA','B10');
xlswrite(FileName,{'Contribution to Total Impact(Absolute)'},'SPA','D10');
xlswrite(FileName,{'Contribution to Total Impact(%)'},'SPA','D10');
xlswrite(FileName,{'Path Sequence'},'SPA','E10');

pathContents = struct2cell(paths); %pathContents is a 2x1xN cell array

seqRank=linspace(1,NumPaths,NumPaths)';
seqLength=zeros(NumPaths,1);
seqVal=zeros(NumPaths,1);
seqContr=zeros(NumPaths,1);

for n=1:2:NumPaths*2
    elRef=(n+1)/2;

    seqVal(elRef,1)=cell2mat(pathContents(n));
    seqContr(elRef,1) = seqVal(elRef,1)/TotalEmissions*100;
    seqTemp=cell2mat(pathContents(n+1));

    pathLength=length(seqTemp); %number of processes in path
    tierDiff=Tmax-pathLength;   %difference between maximum number of
processes and path length

    seqLength(elRef,1)=length(cell2mat(pathContents(n+1)))-1;

    %xlswrite function has problems writing arrays of varying length; fill
    %in 'gaps' in matrix elements with an easily identifiable number and
    %replace with blanks using a macro in Excel
    if tierDiff>0
        for i=1:tierDiff
            seqTemp(Tmax-i+1)=11111;
        end
    end
    seq(elRef,:)=seqTemp;
end
```

```
xlswrite(FileName,seqRank,'SPA','A11');
xlswrite(FileName,seqLength,'SPA','B11');
xlswrite(FileName,seqVal,'SPA','C11');
xlswrite(FileName,seqContr,'SPA','D11');
xlswrite(FileName,seq,'SPA','E11');
```

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Complete SPA Tables

Path Rank	Path Length	Contribution to Total Impact (%)	Path Sequence(Wood→)
Wood			
1	0	32.60	
2	7	16.77	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, softwood, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→'softwood, standing, under bark, in forest'
3	1	15.63	'disposal, wood ash mixture, pure, 0% water, to landfarming'
4	6	10.44	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, hardwood, from industry, u=40%, at plant'→'industrial residue wood, mix, hardwood, u=40%, at plant'→'industrial residue wood, hardwood, including bark, u=70%, at plant'→'round wood, hardwood, under bark, u=70%, at forest road'→'hardwood, standing, under bark, in forest'
5	1	3.55	'disposal, wood ash mixture, pure, 0% water, to sanitary landfill'
6	2	2.71	transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
7	1	1.81	'disposal, wood ash mixture, pure, 0% water, to municipal incineration'
8	3	0.61	'cogen unit 6400kWth, wood burning, components for electricity only'→'control cabinet cogen unit 160kWe'→'light fuel oil, burned in industrial furnace 1MW, non-modulating'
9	7	0.51	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, softwood, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→'softwood, stand establishment / tending / site development, under bark'
10	3	0.45	'cogen unit 6400kWth, wood burning, components for electricity only'→'control cabinet cogen unit 160kWe'→'natural gas, burned in industrial furnace >100kW'
11	7	0.34	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production RAF, at long distance

			transport'→'crude oil, at production onshore'
12	6	0.29	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, hardwood, from industry, u=40%, at plant'→'industrial residue wood, mix, hardwood, u=40%, at plant'→'industrial residue wood, hardwood, including bark, u=70%, at plant'→'round wood, hardwood, under bark, u=70%, at forest road'→'hardwood, stand establishment / tending / site development, under bark'
13	7	0.26	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, softwood, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→'diesel, burned in building machine'
14	7	0.25	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production RME, at long distance transport'→'crude oil, at production onshore'
15	9	0.23	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, hardwood, from industry, u=40%, at plant'→'industrial residue wood, mix, hardwood, u=40%, at plant'→'industrial residue wood, from planing, hard, air/kiln dried, u=10%, at plant'→'sawn timber, hardwood, raw, air / kiln dried, u=10%, at plant'→'sawn timber, hardwood, raw, air dried, u=20%, at plant'→'sawn timber, hardwood, raw, plant-debarked, u=70%, at plant'→'round wood, hardwood, under bark, u=70%, at forest road'→'hardwood, standing, under bark, in forest'
16	8	0.23	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, hardwood, from industry, u=40%, at plant'→'industrial residue wood, mix, hardwood, u=40%, at plant'→'industrial residue wood, from planing, hardwood, kiln dried, u=10%, at plant'→'sawn timber, hardwood, raw, kiln dried, u=10%, at plant'→'sawn timber, hardwood, raw, plant-debarked, u=70%, at plant'→'round wood, hardwood, under bark, u=70%, at forest road'→'hardwood, standing, under bark, in forest'
17	7	0.23	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production NG, at long distance transport'→'crude oil, at production'
18	9	0.22	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, from planing, softwood, air dried, u=20%, at plant'→'sawn timber, softwood, raw, air dried, u=20%, at plant'→'sawn timber, softwood, raw, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest

			road'→'round wood, softwood, under bark, u=70% at forest road'→'softwood, standing, under bark, in forest'
19	9	0.22	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, from planing, softwood, kiln dried, u=10%, at plant'→'sawn timber, softwood, raw, kiln dried, u=10%, at plant'→'sawn timber, softwood, raw, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→'softwood, standing, under bark, in forest'
20	7	0.22	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production NO, at long distance transport'→'crude oil, at production offshore'
21	7	0.18	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production RU, at long distance transport'→'crude oil, at production onshore'
22	7	0.18	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production GB, at long distance transport'→'crude oil, at production offshore'
23	1	0.17	'cogen unit 6400kWth, wood burning, building'
24	9	0.16	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residual wood chopping, stationary electric chopper, at plant'→'electricity, medium voltage, production UCTE, at grid'→'electricity, high voltage, production UCTE, at grid'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, lignite, at power plant'→'lignite, burned in power plant'
25	7	0.16	'cogen unit 6400kWth, wood burning, components for electricity only'→'control cabinet cogen unit 160kWe'→'natural gas, burned in industrial furnace >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'

Wood, EC			
1	0	34.13	
2	7	16.20	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, softwood, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→'softwood, standing, under bark, in forest'
3	1	15.09	'disposal, wood ash mixture, pure, 0% water, to landfarming'
4	6	10.09	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, hardwood, from industry, u=40%, at plant'→'industrial residue wood, mix, hardwood, u=40%, at plant'→'industrial residue wood, hardwood, including bark, u=70%, at plant'→'round wood, hardwood, under bark, u=70%, at forest road'→'hardwood, standing, under bark, in forest'
5	1	3.43	'disposal, wood ash mixture, pure, 0% water, to sanitary landfill'
6	2	2.61	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
7	1	1.75	'disposal, wood ash mixture, pure, 0% water, to municipal incineration'
8	3	0.61	'cogen unit 6400kWth, wood burning, components for electricity only'→'control cabinet cogen unit 160kWe'→'light fuel oil, burned in industrial furnace 1MW, non-modulating'
9	7	0.49	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, softwood, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→'softwood, stand establishment / tending / site development, under bark'
10	3	0.45	'cogen unit 6400kWth, wood burning, components for electricity only'→'control cabinet cogen unit 160kWe'→'natural gas, burned in industrial furnace >100kW'
11	7	0.33	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'
12	6	0.28	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, hardwood, from industry, u=40%, at plant'→'industrial residue wood, mix, hardwood, u=40%, at plant'→'industrial residue wood, hardwood, including bark, u=70%, at plant'→'round wood, hardwood, under bark, u=70%, at forest road'→'hardwood, stand establishment / tending / site development, under bark'

13	7	0.26	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, softwood, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→'diesel, burned in building machine'
14	7	0.24	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production RME, at long distance transport'→'crude oil, at production onshore'
15	9	0.23	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, hardwood, from industry, u=40%, at plant'→'industrial residue wood, mix, hardwood, u=40%, at plant'→'industrial residue wood, from planing, hard, air/kiln dried, u=10%, at plant'→'sawn timber, hardwood, raw, air / kiln dried, u=10%, at plant'→'sawn timber, hardwood, raw, air dried, u=20%, at plant'→'sawn timber, hardwood, raw, plant-debarked, u=70%, at plant'→'round wood, hardwood, under bark, u=70%, at forest road'→
16	8	0.23	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, hardwood, from industry, u=40%, at plant'→'industrial residue wood, mix, hardwood, u=40%, at plant'→'industrial residue wood, from planing, hardwood, kiln dried, u=10%, at plant'→'sawn timber, hardwood, raw, kiln dried, u=10%, at plant'→'sawn timber, hardwood, raw, plant-debarked, u=70%, at plant'→'round wood, hardwood, under bark, u=70%, at forest road'→'hardwood, standing, under bark, in forest'
17	7	0.22	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production NG, at long distance transport'→'crude oil, at production'
18	9	0.21	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, from planing, softwood, air dried, u=20%, at plant'→'sawn timber, softwood, raw, air dried, u=20%, at plant'→'sawn timber, softwood, raw, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→
19	9	0.21	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residue wood, mix, softwood, u=40%, at plant'→'industrial residue wood, from planing, softwood, kiln dried, u=10%, at plant'→'sawn timber, softwood, raw, kiln dried, u=10%, at plant'→'sawn timber, softwood,

			raw, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→
20	7	0.21	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production NO, at long distance transport'→'crude oil, at production offshore'
21	7	0.18	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production RU, at long distance transport'→'crude oil, at production onshore'
22	7	0.18	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production GB, at long distance transport'→'crude oil, at production offshore'
23	1	0.17	'cogen unit 6400kWth, wood burning, building'
24	7	0.16	'cogen unit 6400kWth, wood burning, components for electricity only'→'control cabinet cogen unit 160kWe'→'natural gas, burned in industrial furnace >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'
25	2	0.16	'urea, as N, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'
26	9	0.16	'wood chips, mixed, from industry, u=40%, at plant'→'wood chips, softwood, from industry, u=40%, at plant'→'industrial residual wood chopping, stationary electric chopper, at plant'→'electricity, medium voltage, production UCTE, at grid'→'electricity, high voltage, production UCTE, at grid'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, lignite, at power plant'→

Biogas			
1	2	39.89	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'
2	4	12.43	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'
3	0	5.29	
4	2	4.69	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'
5	8	4.40	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'
6	8	2.15	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NL, at long-distance pipeline'→'natural gas, at production onshore'
7	8	2.13	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NO, at long-distance pipeline'→'natural gas, at production offshore'
8	3	1.88	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'→'transport, municipal waste collection, lorry 21t'
9	8	1.18	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production DZ, at long-distance pipeline'→'natural gas, at production onshore'
10	3	0.92	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'→'disposal, municipal solid waste, 22.9% water, to municipal incineration'
11	5	0.90	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'→'electricity, at cogen with biogas engine, allocation exergy'→'biogas, production mix, at storage'→'biogas, from biowaste, at storage'

12	8	0.85	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NL, at long-distance pipeline'→'natural gas, at production offshore'
13	11	0.85	
14	9	0.70	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'transport, natural gas, pipeline, long distance'→2181
15	10	0.69	
16	8	0.64	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production DE, at long-distance pipeline'→'natural gas, at production onshore'
17	5	0.63	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'→'heat, at cogen with biogas engine, allocation exergy'→'biogas, production mix, at storage'→'biogas, from biowaste, at storage'
18	8	0.52	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production GB, at long-distance pipeline'→'natural gas, at production offshore'
19	8	0.51	'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'transport, natural gas, pipeline, long distance'
20	6	0.28	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'→'anaerobic digestion plant, biowaste'→'concrete, normal, at plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'
21	7	0.28	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'→'electricity, at cogen with biogas engine, allocation

			exergy'→'biogas, production mix, at storage'→'biogas, from sewage sludge, at storage'→'heat, natural gas, at boiler condensing modulating >100kW'→'natural gas, burned in boiler condensing modulating >100kW'
22	4	0.28	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'→'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
23	7	0.24	'biogas, production mix, at storage'→'biogas, from biowaste, at storage'→'transport, municipal waste collection, lorry 21t'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'
24	10	0.22	
25	1	0.21	'disposal, used mineral oil, 10% water, to hazardous waste incineration'

Bioethanol, sorghum			
1	1	55.01	'sweet sorghum stem, at farm'
2	0	8.56	
3	1	4.33	'disposal, wood ash mixture, pure, 0% water, to landfarming'
4	3	1.94	'sweet sorghum stem, at farm'→'ammonium nitrate, as N, at regional storehouse'→'nitric acid, 50% in H2O, at plant'
5	3	1.38	'sweet sorghum stem, at farm'→'irrigating'→'polyethylene, HDPE, granulate, at plant'
6	2	1.31	'sweet sorghum stem, at farm'→'combine harvesting'
7	2	1.16	'transport, lorry >16t, fleet average'→'operation, lorry >16t, fleet average'
8	2	0.99	'sweet sorghum stem, at farm'→'tillage, ploughing'
9	1	0.98	'disposal, wood ash mixture, pure, 0% water, to sanitary landfill'
10	3	0.61	'sweet sorghum stem, at farm'→'urea, as N, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'
11	2	0.59	'sweet sorghum stem, at farm'→'tillage, cultivating, chiselling'
12	1	0.50	'disposal, wood ash mixture, pure, 0% water, to municipal incineration'
13	3	0.30	'sweet sorghum stem, at farm'→'ammonium nitrate, as N, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'
14	5	0.28	'sweet sorghum stem, at farm'→'ammonium nitrate, as N, at regional storehouse'→'nitric acid, 50% in H2O, at plant'→'ammonia, liquid, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'
15	3	0.27	'sweet sorghum stem, at farm'→'transport, barge'→'operation, barge'
16	2	0.25	'sweet sorghum stem, at farm'→'irrigating'
17	3	0.21	'sweet sorghum stem, at farm'→'transport, lorry >16t, fleet average'→'operation, lorry >16t, fleet average'
18	5	0.19	'sweet sorghum stem, at farm'→'irrigating'→'agricultural machinery, general, production'→'steel, converter, unalloyed, at plant'→'pig iron, at plant'
19	7	0.18	'sweet sorghum stem, at farm'→'urea, as N, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'
20	9	0.18	'sweet sorghum stem, at farm'→'irrigating'→'shed'→'sawn timber, softwood, planed, air dried, at plant'→'sawn timber, softwood, raw, air dried, u=20%, at plant'→'sawn timber, softwood, raw, forest-debarked, u=70%, at plant'→'round wood, softwood, debarked, u=70% at forest road'→'round wood, softwood, under bark, u=70% at forest road'→3588
21	2	0.17	'sweet sorghum stem, at farm'→'tillage, harrowing, by spring tine harrow'

22	2	0.16	'transport, lorry 3.5-16t, fleet average'→'operation, lorry 3.5-16t, fleet average'
23	4	0.15	'sweet sorghum stem, at farm'→'urea, as N, at regional storehouse'→'heat, natural gas, at industrial furnace >100kW'→'natural gas, burned in industrial furnace >100kW'
24	5	0.15	'sweet sorghum stem, at farm'→'diammonium phosphate, as P2O5, at regional storehouse'→'phosphoric acid, fertiliser grade, 70% in H2O, at plant'→'sulphuric acid, liquid, at plant'→'secondary sulphur, at refinery'
25	4	0.15	'sweet sorghum stem, at farm'→'diammonium phosphate, as P2O5, at regional storehouse'→'phosphoric acid, fertiliser grade, 70% in H2O, at plant'→'sulphuric acid, liquid, at plant'

Bioethanol, wood			
1	3	62.48	'wood chips, hardwood, u=80%, at forest'→'industrial wood, hardwood, under bark, u=80%, at forest road'→'hardwood, standing, under bark, in forest'
2	0	5.44	
3	2	2.42	'ammonia, liquid, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'
4	1	2.40	'disposal, wood ash mixture, pure, 0% water, to landfarming'
5	2	2.25	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
6	3	1.71	'wood chips, hardwood, u=80%, at forest'→'industrial wood, hardwood, under bark, u=80%, at forest road'→'hardwood, stand establishment / tending / site development, under bark'
7	3	1.67	'wood chips, hardwood, u=80%, at forest'→'wood chopping, mobile chopper, in forest'→'diesel, burned in building machine'
8	1	0.83	'quicklime, in pieces, loose, at plant'
9	2	0.81	'ammonia, liquid, at regional storehouse'→'ammonia, partial oxidation, liquid, at plant'
10	2	0.73	'maize starch, at plant'→'grain maize IP, at farm'
11	6	0.73	'ammonia, liquid, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'
12	3	0.72	'maize starch, at plant'→'grain maize IP, at farm'→'green manure IP, until April'
13	1	0.54	'disposal, wood ash mixture, pure, 0% water, to sanitary landfill'
14	6	0.36	'ammonia, liquid, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NL, at long-distance pipeline'→'natural gas, at production onshore'
15	6	0.35	'ammonia, liquid, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NO, at long-distance pipeline'→'natural gas, at production offshore'
16	2	0.34	'sulphuric acid, liquid, at plant'→'secondary sulphur, at refinery'
17	1	0.33	'sulphuric acid, liquid, at plant'
18	7	0.28	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'

19	1	0.28	'disposal, wood ash mixture, pure, 0% water, to municipal incineration'
20	3	0.27	'wood chips, hardwood, u=80%, at forest'→'industrial wood, hardwood, under bark, u=80%, at forest road'→'diesel, burned in building machine'
21	7	0.22	'wood chips, hardwood, u=80%, at forest'→'wood chopping, mobile chopper, in forest'→'diesel, burned in building machine'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production RME, at long distance transport'→'crude oil, at production onshore'
22	7	0.21	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'→'diesel, low-sulphur, at regional storage'→'diesel, low-sulphur, at refinery'→'diesel, at refinery'→'crude oil, production RME, at long distance transport'→'crude oil, at production onshore'
23	1	0.20	'transport, tractor and trailer'
24	6	0.19	'ammonia, liquid, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production DZ, at long-distance pipeline'→'natural gas, at production onshore'
25	7	0.19	'wood chips, hardwood, u=80%, at forest'→'wood chopping, mobile chopper, in forest'→'diesel, burned in building machine'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production NO, at long distance transport'→'crude oil, at production offshore'

Biowaste			
1	0	24.02	
2	1	11.96	'transport, municipal waste collection, lorry 21t'
3	1	8.05	'process-specific burdens, municipal waste incineration'
4	2	2.47	'process-specific burdens, municipal waste incineration'→'natural gas, burned in industrial furnace low-NOx >100kW'
5	3	2.32	'cement, unspecified, at plant'→'portland calcareous cement, at plant'→'clinker, at plant'
6	3	2.13	'cement, unspecified, at plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'
7	5	1.54	'transport, municipal waste collection, lorry 21t'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'
8	2	1.14	'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
9	5	1.13	'transport, municipal waste collection, lorry 21t'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production RME, at long distance transport'→'crude oil, at production onshore'
10	5	1.05	'transport, municipal waste collection, lorry 21t'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production NG, at long distance transport'→'crude oil, at production'
11	5	1.01	'transport, municipal waste collection, lorry 21t'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production NO, at long distance transport'→'crude oil, at production offshore'
12	1	0.99	'natural gas, burned in industrial furnace low-NOx >100kW'
13	6	0.87	'process-specific burdens, municipal waste incineration'→'natural gas, burned in industrial furnace low-NOx >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'
14	5	0.84	'transport, municipal waste collection, lorry 21t'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production RU, at long distance transport'→'crude oil, at production onshore'
15	5	0.84	'transport, municipal waste collection, lorry 21t'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production GB, at long distance transport'→'crude oil, at production offshore'
16	3	0.59	'process-specific burdens, municipal waste incineration'→'ammonia, liquid, at regional storehouse'→'ammonia, steam reforming, liquid, at plant'
17	3	0.57	'quicklime, milled, packed, at plant'→'quicklime, milled, loose, at plant'→'quicklime, in pieces, loose, at plant'
18	3	0.53	'process-specific burdens, municipal waste incineration'→'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'

19	5	0.48	'transport, municipal waste collection, lorry 21t'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'
20	6	0.43	'process-specific burdens, municipal waste incineration'→'natural gas, burned in industrial furnace low-NOx >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NL, at long-distance pipeline'→'natural gas, at production onshore'
21	4	0.42	'municipal waste incineration plant'→'reinforcing steel, at plant'→'steel, converter, unalloyed, at plant'→'pig iron, at plant'
22	6	0.42	'process-specific burdens, municipal waste incineration'→'natural gas, burned in industrial furnace low-NOx >100kW'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NO, at long-distance pipeline'→'natural gas, at production offshore'
23	3	0.41	'municipal waste incineration plant'→'disposal, building, bitumen sheet, to final disposal'→'disposal, bitumen sheet, 1.5% water, to municipal incineration'
24	4	0.38	'municipal waste incineration plant'→'cement, unspecified, at plant'→'portland calcareous cement, at plant'→'clinker, at plant'
25	2	0.35	'process-specific burdens, slag compartment'→'diesel, burned in building machine'

Wind, average			
1	4	8.44	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'glass fibre reinforced plastic, polyamide, injection moulding, at plant'→'nylon 66, glass-filled, at plant'
2	4	6.31	'electricity, at wind power plant 800kW'→'wind power plant 800kW, moving parts'→'glass fibre reinforced plastic, polyamide, injection moulding, at plant'→'nylon 66, glass-filled, at plant'
3	2	1.90	'electricity, at wind power plant 600kW'→'wind power plant 600kW, fixed parts'
4	6	1.40	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
5	6	1.22	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
6	5	1.07	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'
7	2	1.01	'electricity, at wind power plant 800kW'→'wind power plant 800kW, fixed parts'
8	5	0.88	'electricity, at wind power plant 600kW'→'wind power plant 600kW, fixed parts'→'concrete, normal, at plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'
9	5	0.85	'electricity, at wind power plant 600kW'→'wind power plant 600kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'
10	4	0.83	'electricity, at wind power plant Grenchenberg 150kW'→'wind power plant 150kW, moving parts'→'glass fibre reinforced plastic, polyamide, injection moulding, at plant'→'nylon 66, glass-filled, at plant'
11	6	0.82	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
12	5	0.79	'electricity, at wind power plant 800kW'→'wind power plant 800kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'
13	6	0.76	'electricity, at wind power plant 800kW'→'wind power plant 800kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic

			tailings, off-site'
14	2	0.75	'electricity, at wind power plant Simplon 30kW'→'wind power plant 30kW, fixed parts'
15	4	0.75	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'
16	5	0.72	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'
17	6	0.63	'electricity, at wind power plant 800kW'→'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
18	5	0.63	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'
19	5	0.57	'electricity, at wind power plant 800kW'→'wind power plant 800kW, fixed parts'→'concrete, normal, at plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'
20	5	0.54	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'copper, at regional storage'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
21	3	0.52	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'disposal, plastics, mixture, 15.3% water, to municipal incineration'
22	6	0.51	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'natural gas, burned in industrial furnace >100kW'
23	5	0.48	'electricity, at wind power plant 800kW'→'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'
24	6	0.47	'electricity, at wind power plant 600kW'→'wind power plant 600kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper, SX-EW, at refinery'→'disposal, sulfidic tailings, off-site'
25	4	0.47	'electricity, at wind power plant 800kW'→'wind power plant 800kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'

Wind, Offshore			
1	3	16.97	'wind power plant 2MW, offshore, moving parts'→'glass fibre reinforced plastic, polyamide, injection moulding, at plant'→'nylon 66, glass-filled, at plant'
2	4	6.20	'wind power plant 2MW, offshore, fixed parts'→'concrete, normal, at plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'
3	4	1.76	'wind power plant 2MW, offshore, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'
4	5	1.42	'wind power plant 2MW, offshore, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
5	5	1.28	'wind power plant 2MW, offshore, fixed parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
6	4	1.16	'wind power plant 2MW, offshore, fixed parts'→'reinforcing steel, at plant'→'steel, converter, unalloyed, at plant'→'pig iron, at plant'
7	4	1.08	'wind power plant 2MW, offshore, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'
8	2	1.02	'wind power plant 2MW, offshore, moving parts'→'disposal, plastics, mixture, 15.3% water, to municipal incineration'
9	2	0.97	'wind power plant 2MW, offshore, fixed parts'→'excavation, hydraulic digger'
10	5	0.83	'wind power plant 2MW, offshore, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
11	3	0.79	'wind power plant 2MW, offshore, fixed parts'→'copper, at regional storage'→'copper, primary, at refinery'
12	4	0.73	'wind power plant 2MW, offshore, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'
13	8	0.69	'wind power plant 2MW, offshore, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'hard coal coke, at plant'→'hard coal mix, at regional storage'→'hard coal, at regional storage'→'hard coal, at mine'
14	5	0.64	'wind power plant 2MW, offshore, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'sinter, iron, at plant'
15	4	0.64	'wind power plant 2MW, offshore, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'

16	7	0.63	'wind power plant 2MW, offshore, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'sinter, iron, at plant'→'iron ore, 65% Fe, at beneficiation'→'iron ore, 46% Fe, at mine'
17	4	0.57	'wind power plant 2MW, offshore, fixed parts'→'copper, at regional storage'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
18	3	0.57	'wind power plant 2MW, offshore, fixed parts'→'transport, lorry >16t, fleet average'→'operation, lorry >16t, fleet average'
19	3	0.55	'wind power plant 2MW, offshore, fixed parts'→'steel, low-alloyed, at plant'→'steel, electric, un- and low-alloyed, at plant'
20	5	0.52	'wind power plant 2MW, offshore, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
21	5	0.52	'wind power plant 2MW, offshore, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'natural gas, burned in industrial furnace >100kW'
22	1	0.51	'disposal, used mineral oil, 10% water, to hazardous waste incineration'
23	6	0.50	'wind power plant 2MW, offshore, fixed parts'→'concrete, normal, at plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'→'hard coal, at regional storage'→'hard coal, at mine'
24	5	0.49	'wind power plant 2MW, offshore, fixed parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper, SX-EW, at refinery'→'disposal, sulfidic tailings, off-site'
25	3	0.48	'wind power plant 2MW, offshore, moving parts'→'cast iron, at plant'→'pig iron, at plant'

Wind, 600 kW			
1	3	14.87	'wind power plant 600kW, moving parts'→'glass fibre reinforced plastic, polyamide, injection moulding, at plant'→'nylon 66, glass-filled, at plant'
2	1	3.34	'wind power plant 600kW, fixed parts'
3	5	2.46	'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
4	5	2.15	'wind power plant 600kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
5	4	1.88	'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'
6	4	1.56	'wind power plant 600kW, fixed parts'→'concrete, normal, at plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'
7	4	1.50	'wind power plant 600kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'
8	5	1.45	'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
9	3	1.32	'wind power plant 600kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'
10	4	1.26	'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'
11	4	1.10	'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'
12	4	0.95	'wind power plant 600kW, moving parts'→'copper, at regional storage'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
13	2	0.92	'wind power plant 600kW, moving parts'→'disposal, plastics, mixture, 15.3% water, to municipal incineration'
14	5	0.90	'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'natural gas, burned in industrial furnace >100kW'
15	5	0.83	'wind power plant 600kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper, SX-EW, at refinery'→'disposal, sulfidic tailings, off-site'
16	4	0.76	'wind power plant 600kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'pig iron, at plant'

17	4	0.74	'wind power plant 600kW, moving parts'⟶'chromium steel 18/8, at plant'⟶'steel, electric, chromium steel 18/8, at plant'⟶'ferronickel, 25% Ni, at plant'
18	3	0.67	'wind power plant 600kW, moving parts'⟶'cast iron, at plant'⟶'pig iron, at plant'
19	5	0.67	'wind power plant 600kW, moving parts'⟶'copper, at regional storage'⟶'copper, primary, at refinery'⟶'copper concentrate, at beneficiation'⟶'disposal, sulfidic tailings, off-site'
20	8	0.59	'wind power plant 600kW, fixed parts'⟶'steel, low-alloyed, at plant'⟶'steel, converter, low-alloyed, at plant'⟶'pig iron, at plant'⟶'hard coal coke, at plant'⟶'hard coal mix, at regional storage'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
21	5	0.55	'wind power plant 600kW, fixed parts'⟶'steel, low-alloyed, at plant'⟶'steel, converter, low-alloyed, at plant'⟶'pig iron, at plant'⟶'sinter, iron, at plant'
22	2	0.54	'wind power plant 600kW, moving parts'⟶'polyethylene, HDPE, granulate, at plant'
23	7	0.53	'wind power plant 600kW, fixed parts'⟶'steel, low-alloyed, at plant'⟶'steel, converter, low-alloyed, at plant'⟶'pig iron, at plant'⟶'sinter, iron, at plant'⟶'iron ore, 65% Fe, at beneficiation'⟶'iron ore, 46% Fe, at mine'
24	8	0.53	'wind power plant 600kW, moving parts'⟶'chromium steel 18/8, at plant'⟶'steel, converter, chromium steel 18/8, at plant'⟶'ferronickel, 25% Ni, at plant'⟶'hard coal, burned in industrial furnace 1-10MW'⟶'hard coal mix, at regional storage'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
25	5	0.53	'wind power plant 600kW, moving parts'⟶'chromium steel 18/8, at plant'⟶'steel, electric, chromium steel 18/8, at plant'⟶'ferronickel, 25% Ni, at plant'⟶'natural gas, burned in industrial furnace >100kW'

Wind, 800 kW			
1	3	17.57	'wind power plant 800kW, moving parts'→'glass fibre reinforced plastic, polyamide, injection moulding, at plant'→'nylon 66, glass-filled, at plant'
2	1	2.82	'wind power plant 800kW, fixed parts'
3	4	2.20	'wind power plant 800kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'
4	5	2.11	'wind power plant 800kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
5	5	1.75	'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
6	4	1.59	'wind power plant 800kW, fixed parts'→'concrete, normal, at plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'
7	4	1.34	'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'
8	3	1.30	'wind power plant 800kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'
9	2	1.08	'wind power plant 800kW, moving parts'→'disposal, plastics, mixture, 15.3% water, to municipal incineration'
10	5	1.03	'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
11	4	0.94	'wind power plant 800kW, moving parts'→'copper, at regional storage'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
12	4	0.90	'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'
13	8	0.86	'wind power plant 800kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'hard coal coke, at plant'→'hard coal mix, at regional storage'→'hard coal, at regional storage'→'hard coal, at mine'
14	5	0.81	'wind power plant 800kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper, SX-EW, at refinery'→'disposal, sulfidic tailings, off-site'
15	5	0.80	'wind power plant 800kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'sinter, iron, at plant'
16	4	0.79	'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'

17	7	0.78	'wind power plant 800kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'sinter, iron, at plant'→'iron ore, 65% Fe, at beneficiation'→'iron ore, 46% Fe, at mine'
18	3	0.68	'wind power plant 800kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, electric, un- and low-alloyed, at plant'
19	5	0.66	'wind power plant 800kW, moving parts'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
20	5	0.64	'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'natural gas, burned in industrial furnace >100kW'
21	5	0.59	'wind power plant 800kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
22	4	0.54	'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'pig iron, at plant'
23	4	0.53	'wind power plant 800kW, moving parts'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'
24	3	0.52	'wind power plant 800kW, moving parts'→'cast iron, at plant'→'pig iron, at plant'
25	8	0.51	'wind power plant 800kW, fixed parts'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'hard coal coke, at plant'→'hard coal mix, at regional storage'→'hard coal, at regional storage'→'hard coal, at mine'

Hydro, pumped			
1	6	5.10	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, lignite, at power plant'→'lignite, burned in power plant'
2	6	3.62	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'
3	7	2.86	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, lignite, at power plant'→'lignite, burned in power plant'→'lignite, at mine'
4	6	2.66	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix PL'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'
5	6	2.41	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix ES'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'
6	8	2.14	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, lignite, at power plant'→'lignite, burned in power plant'→'lignite, at mine'→'disposal, spoil from lignite mining, in surface landfill'
7	9	2.10	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'→'hard coal supply mix'→'hard coal, at regional storage'→
8	6	2.00	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix IT'→'electricity, natural gas, at power plant'→'natural gas, burned in power plant'
9	6	1.89	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix PL'→'electricity, lignite, at power plant'→'lignite, burned in power plant'
10	9	1.82	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix PL'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'→'hard coal supply mix'→'hard coal, at regional storage'→
11	4	1.64	'electricity, high voltage, at grid'→'electricity mix'→'electricity, natural gas, at power plant'→'natural gas, burned in power plant'
12	6	1.44	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix GR'→'electricity, lignite, at power plant'→'lignite, burned in power plant'
13	6	1.42	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix CZ'→'electricity, lignite, at power plant'→'lignite, burned in power plant'

14	6	1.38	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix CS'→'electricity, lignite, at power plant'→'lignite, burned in power plant'
15	6	1.28	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix IT'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'
16	6	1.26	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix IT'→'electricity, oil, at power plant'→'heavy fuel oil, burned in power plant'
17	4	1.16	'electricity, high voltage, at grid'→'electricity mix'→'electricity, oil, at power plant'→'heavy fuel oil, burned in power plant'
18	7	1.01	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix GR'→'electricity, lignite, at power plant'→'lignite, burned in power plant'→'lignite, at mine'
19	7	0.99	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix PL'→'electricity, lignite, at power plant'→'lignite, burned in power plant'→'lignite, at mine'
20	6	0.95	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix NL'→'electricity, natural gas, at power plant'→'natural gas, burned in power plant'
21	6	0.79	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, natural gas, at power plant'→'natural gas, burned in power plant'
22	6	0.79	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix FR'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'
23	8	0.75	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix GR'→'electricity, lignite, at power plant'→'lignite, burned in power plant'→'lignite, at mine'→'disposal, spoil from lignite mining, in surface landfill'
24	8	0.74	'electricity, high voltage, at grid'→'electricity mix'→'electricity, production mix UCTE'→'electricity, production mix PL'→'electricity, lignite, at power plant'→'lignite, burned in power plant'→'lignite, at mine'→'disposal, spoil from lignite mining, in surface landfill'
25	3	0.70	'reservoir hydropower plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'

Hydro, reservoir			
1	3	26.42	'reservoir hydropower plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'
2	0	11.16	
3	1	5.20	'reservoir hydropower plant'
4	2	3.05	'reservoir hydropower plant'→'disposal, building, reinforced concrete, to final disposal'
5	3	2.31	'reservoir hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'diesel, burned in building machine'
6	5	2.13	'reservoir hydropower plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'→'hard coal, at regional storage'→'hard coal, at mine'
7	2	2.11	'reservoir hydropower plant'→'diesel, burned in building machine'
8	4	1.38	'reservoir hydropower plant'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'
9	4	-1.10	'reservoir hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'disposal, inert waste, 5% water, to inert material landfill'→'process-specific burdens, inert material landfill'
10	7	1.05	'reservoir hydropower plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'→'heavy fuel oil, at regional storage'→'heavy fuel oil, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'
11	5	0.99	'reservoir hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'disposal, inert waste, 5% water, to inert material landfill'→'process-specific burdens, inert material landfill'→'diesel, burned in building machine'
12	4	0.90	'reservoir hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
13	7	0.81	'reservoir hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'disposal, inert waste, 5% water, to inert material landfill'→'inert material landfill facility'→'bitumen, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'
14	6	0.79	'reservoir hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'disposal, inert waste, 5% water, to inert material landfill'→'inert material landfill facility'→'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
15	7	0.71	'reservoir hydropower plant'→'portland cement, strength class Z

			42.5, at plant'→'clinker, at plant'→'heavy fuel oil, at regional storage'→'heavy fuel oil, at refinery'→'crude oil, production NG, at long distance transport'→'crude oil, at production'
16	5	0.66	'reservoir hydropower plant'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
17	7	0.55	'reservoir hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'disposal, inert waste, 5% water, to inert material landfill'→'inert material landfill facility'→'bitumen, at refinery'→'crude oil, production NG, at long distance transport'→'crude oil, at production'
18	8	0.54	'reservoir hydropower plant'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'hard coal coke, at plant'→'hard coal mix, at regional storage'→'hard coal, at regional storage'→'hard coal, at mine'
19	5	0.50	'reservoir hydropower plant'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'sinter, iron, at plant'
20	4	0.50	'reservoir hydropower plant'→'chromium steel 18/8, at plant'→'steel, converter, chromium steel 18/8, at plant'→'ferrochromium, high-carbon, 68% Cr, at plant'
21	7	0.49	'reservoir hydropower plant'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'sinter, iron, at plant'→'iron ore, 65% Fe, at beneficiation'→'iron ore, 46% Fe, at mine'
22	3	0.47	'reservoir hydropower plant'→'gravel, round, at mine'→'diesel, burned in building machine'
23	2	0.43	'reservoir hydropower plant'→'gravel, round, at mine'
24	3	0.43	'reservoir hydropower plant'→'steel, low-alloyed, at plant'→'steel, electric, un- and low-alloyed, at plant'
25	5	0.38	'reservoir hydropower plant'→'chromium steel 18/8, at plant'→'steel, electric, chromium steel 18/8, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'

Hydro, run-of-river			
1	3	18.55	'run-of-river hydropower plant'⟶'portland cement, strength class Z 42.5, at plant'⟶'clinker, at plant'
2	1	15.18	'run-of-river hydropower plant'
3	2	6.47	'run-of-river hydropower plant'⟶'diesel, burned in building machine'
4	4	2.49	'run-of-river hydropower plant'⟶'steel, low-alloyed, at plant'⟶'steel, converter, low-alloyed, at plant'⟶'pig iron, at plant'
5	2	2.10	'run-of-river hydropower plant'⟶'disposal, building, reinforced concrete, to final disposal'
6	3	1.59	'run-of-river hydropower plant'⟶'disposal, building, reinforced concrete, to final disposal'⟶'diesel, burned in building machine'
7	5	1.50	'run-of-river hydropower plant'⟶'portland cement, strength class Z 42.5, at plant'⟶'clinker, at plant'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
8	8	0.97	'run-of-river hydropower plant'⟶'steel, low-alloyed, at plant'⟶'steel, converter, low-alloyed, at plant'⟶'pig iron, at plant'⟶'hard coal coke, at plant'⟶'hard coal mix, at regional storage'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
9	4	0.92	'run-of-river hydropower plant'⟶'reinforcing steel, at plant'⟶'steel, converter, unalloyed, at plant'⟶'pig iron, at plant'
10	5	0.90	'run-of-river hydropower plant'⟶'steel, low-alloyed, at plant'⟶'steel, converter, low-alloyed, at plant'⟶'pig iron, at plant'⟶'sinter, iron, at plant'
11	7	0.88	'run-of-river hydropower plant'⟶'steel, low-alloyed, at plant'⟶'steel, converter, low-alloyed, at plant'⟶'pig iron, at plant'⟶'sinter, iron, at plant'⟶'iron ore, 65% Fe, at beneficiation'⟶'iron ore, 46% Fe, at mine'
12	6	0.84	'run-of-river hydropower plant'⟶'diesel, burned in building machine'⟶'diesel, at regional storage'⟶'diesel, at refinery'⟶'crude oil, production RME, at long distance transport'⟶'crude oil, at production onshore'
13	3	0.77	'run-of-river hydropower plant'⟶'steel, low-alloyed, at plant'⟶'steel, electric, un- and low-alloyed, at plant'
14	4	-0.76	'run-of-river hydropower plant'⟶'disposal, building, reinforced concrete, to final disposal'⟶'disposal, inert waste, 5% water, to inert material landfill'⟶'process-specific burdens, inert material landfill'
15	6	0.74	'run-of-river hydropower plant'⟶'diesel, burned in building machine'⟶'diesel, at regional storage'⟶'diesel, at refinery'⟶'crude oil, production NO, at long distance transport'⟶'crude oil, at production offshore'

16	7	0.74	'run-of-river hydropower plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'→'heavy fuel oil, at regional storage'→'heavy fuel oil, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'
17	5	0.68	'run-of-river hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'disposal, inert waste, 5% water, to inert material landfill'→'process-specific burdens, inert material landfill'→'diesel, burned in building machine'
18	5	0.67	'run-of-river hydropower plant'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'ferronickel, 25% Ni, at plant'→'hard coal, burned in industrial furnace 1-10MW'
19	6	0.62	'run-of-river hydropower plant'→'diesel, burned in building machine'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production RU, at long distance transport'→'crude oil, at production onshore'
20	4	0.62	'run-of-river hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
21	6	0.62	'run-of-river hydropower plant'→'diesel, burned in building machine'→'diesel, at regional storage'→'diesel, at refinery'→'crude oil, production GB, at long distance transport'→'crude oil, at production offshore'
22	8	0.57	'run-of-river hydropower plant'→'steel, low-alloyed, at plant'→'steel, converter, low-alloyed, at plant'→'pig iron, at plant'→'hard coal coke, at plant'→'hard coal mix, at regional storage'→'hard coal, at regional storage'→'hard coal, at mine'
23	7	0.56	'run-of-river hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'disposal, inert waste, 5% water, to inert material landfill'→'inert material landfill facility'→'bitumen, at refinery'→'crude oil, production RAF, at long distance transport'→'crude oil, at production onshore'
24	6	0.54	'run-of-river hydropower plant'→'disposal, building, reinforced concrete, to final disposal'→'disposal, inert waste, 5% water, to inert material landfill'→'inert material landfill facility'→'transport, lorry 20-28t, fleet average'→'operation, lorry 20-28t, fleet average'
25	7	0.50	'run-of-river hydropower plant'→'portland cement, strength class Z 42.5, at plant'→'clinker, at plant'→'heavy fuel oil, at regional storage'→'heavy fuel oil, at refinery'→'crude oil, production NG, at long distance transport'→'crude oil, at production'

PV, multi-Si			
1	8	4.44	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'→'multi-Si wafer, at plant'→'silicon, multi-Si, casted, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'
2	3	3.38	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'
3	8	2.22	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'→'multi-Si wafer, at plant'→'silicon, multi-Si, casted, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, electronic grade, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'
4	3	2.08	'3kWp flat roof installation, multi-Si, on roof'→'flat roof construction, on roof'→'polyethylene, HDPE, granulate, at plant'
5	5	1.75	'3kWp flat roof installation, multi-Si, on roof'→'flat roof construction, on roof'→'aluminium, production mix, wrought alloy, at plant'→'aluminium, primary, at plant'→'aluminium, primary, liquid, at plant'
6	4	1.66	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'solar glass, low-iron, at regional storage'→'flat glass, uncoated, at plant'
7	12	1.36	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'→'multi-Si wafer, at plant'→'silicon, multi-Si, casted, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'
8	6	1.28	'3kWp flat roof installation, multi-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
9	6	1.15	'3kWp flat roof installation, multi-Si, on roof'→'inverter, 2500W, at plant'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
10	4	1.06	'3kWp flat roof installation, multi-Si, on roof'→'flat roof

			construction, on roof'→'disposal, building, polyethylene/polypropylene products, to final disposal'→'disposal, polyethylene, 0.4% water, to municipal incineration'
11	4	0.98	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'aluminium alloy, AlMg3, at plant'→'magnesium, at plant'
12	8	0.88	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'→'multi-Si wafer, at plant'→'silicon, multi-Si, casted, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'MG-silicon, at plant'
13	8	0.84	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'→'multi-Si wafer, at plant'→'silicon, multi-Si, casted, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'heat, at cogen 1MWe lean burn, allocation exergy'
14	3	0.84	'3kWp flat roof installation, multi-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'polyethylene, HDPE, granulate, at plant'
15	5	0.81	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'ethylvinylacetate, foil, at plant'→'ethylene vinyl acetate copolymer, at plant'→'ethylene, average, at plant'
16	4	0.79	'3kWp flat roof installation, multi-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'copper, at regional storage'→'copper, primary, at refinery'
17	3	0.74	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'disposal, plastics, mixture, 15.3% water, to municipal incineration'
18	4	0.71	'3kWp flat roof installation, multi-Si, on roof'→'inverter, 2500W, at plant'→'copper, at regional storage'→'copper, primary, at refinery'
19	12	0.68	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'→'multi-Si wafer, at plant'→'silicon, multi-Si, casted, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, electronic grade, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at

			production onshore'
20	12	0.67	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'→'multi-Si wafer, at plant'→'silicon, multi-Si, casted, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NL, at long-distance pipeline'→'natural gas, at production onshore'
21	12	0.66	'3kWp flat roof installation, multi-Si, on roof'→'photovoltaic panel, multi-Si, at plant'→'photovoltaic cell, multi-Si, at plant'→'multi-Si wafer, at plant'→'silicon, multi-Si, casted, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NO, at long-distance pipeline'→'natural gas, at production offshore'
22	3	0.61	'3kWp flat roof installation, multi-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'disposal, plastic, industr. electronics, 15.3% water, to municipal incineration'
23	5	0.57	'3kWp flat roof installation, multi-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'copper, at regional storage'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
24	11	0.56	'3kWp flat roof installation, multi-Si, on roof'→'flat roof construction, on roof'→'aluminium, production mix, wrought alloy, at plant'→'aluminium, primary, at plant'→'aluminium, primary, liquid, at plant'→'electricity, medium voltage, aluminium industry, at grid'→'electricity, high voltage, aluminium industry, at grid'→'electricity mix, aluminium industry'→'electricity, hard coal, at power plant'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'
25	2	0.51	'3kWp flat roof installation, multi-Si, on roof'→'operation, lorry 20-28t, empty, fleet average'

PV, Single Si			
1	8	3.39	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'
2	3	2.92	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'
3	3	1.79	'3kWp flat roof installation, single-Si, on roof'→'flat roof construction, on roof'→'polyethylene, HDPE, granulate, at plant'
4	8	1.70	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, electronic grade, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'
5	5	1.51	'3kWp flat roof installation, single-Si, on roof'→'flat roof construction, on roof'→'aluminium, production mix, wrought alloy, at plant'→'aluminium, primary, at plant'→'aluminium, primary, liquid, at plant'
6	4	1.43	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'solar glass, low-iron, at regional storage'→'flat glass, uncoated, at plant'
7	6	1.17	'3kWp flat roof installation, single-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
8	6	1.06	'3kWp flat roof installation, single-Si, on roof'→'inverter, 2500W, at plant'→'copper, at regional storage'→'copper, primary, at refinery'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'
9	11	1.04	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'electricity, medium voltage, production UCTE, at grid'→'electricity, high voltage, production UCTE, at grid'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity,

			lignite, at power plant'→'lignite, burned in power plant'
10	12	1.04	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'electricity, at cogen 1MWe lean burn, allocation exergy'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'
11	4	0.91	'3kWp flat roof installation, single-Si, on roof'→'flat roof construction, on roof'→'disposal, building, polyethylene/polypropylene products, to final disposal'→'disposal, polyethylene, 0.4% water, to municipal incineration'
12	4	0.84	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'aluminium alloy, AlMg3, at plant'→'magnesium, at plant'
13	3	0.77	'3kWp flat roof installation, single-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'polyethylene, HDPE, granulate, at plant'
14	11	0.74	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'electricity, medium voltage, production UCTE, at grid'→'electricity, high voltage, production UCTE, at grid'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'
15	4	0.72	'3kWp flat roof installation, single-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'copper, at regional storage'→'copper, primary, at refinery'
16	5	0.70	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'ethylvinylacetate, foil, at plant'→'ethylene vinyl acetate copolymer, at plant'→'ethylene, average, at plant'
17	8	0.67	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade,

			modified Siemens process, at plant'→'MG-silicon, at plant'
18	6	0.65	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'natural gas, burned in industrial furnace low-NOx >100kW'
19	4	0.65	'3kWp flat roof installation, single-Si, on roof'→'inverter, 2500W, at plant'→'copper, at regional storage'→'copper, primary, at refinery'
20	8	0.64	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'silicon, production mix, photovoltaics, at plant'→'silicon, solar grade, modified Siemens process, at plant'→'heat, at cogen 1MWe lean burn, allocation exergy'
21	3	0.64	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'disposal, plastics, mixture, 15.3% water, to municipal incineration'
22	12	0.58	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'electricity, medium voltage, production UCTE, at grid'→'electricity, high voltage, production UCTE, at grid'→'electricity, production mix UCTE'→'electricity, production mix DE'→'electricity, lignite, at power plant'→'lignite, burned in power plant'→'lignite, at mine'
23	3	0.56	'3kWp flat roof installation, single-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'disposal, plastic, industr. electronics, 15.3% water, to municipal incineration'
24	11	0.54	'3kWp flat roof installation, single-Si, on roof'→'photovoltaic panel, single-Si, at plant'→'photovoltaic cell, single-Si, at plant'→'single-Si wafer, photovoltaics, at plant'→'CZ single crystalline silicon, photovoltaics, at plant'→'electricity, medium voltage, production UCTE, at grid'→'electricity, high voltage, production UCTE, at grid'→'electricity, production mix UCTE'→'electricity, production mix PL'→'electricity, hard coal, at power plant'→'hard coal, burned in power plant'
25	5	0.52	'3kWp flat roof installation, single-Si, on roof'→'electric installation, photovoltaic plant, at plant'→'copper, at regional storage'→'copper concentrate, at beneficiation'→'disposal, sulfidic tailings, off-site'

NGCC			
1	1	42.22	'natural gas, burned in combined cycle plant, best technology'
2	5	14.83	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'
3	5	7.26	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NL, at long-distance pipeline'→'natural gas, at production onshore'
4	5	7.16	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NO, at long-distance pipeline'→'natural gas, at production offshore'
5	5	3.96	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production DZ, at long-distance pipeline'→'natural gas, at production onshore'
6	5	2.88	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NL, at long-distance pipeline'→'natural gas, at production offshore'
7	8	2.87	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production DZ, at long-distance pipeline'→'natural gas, production DZ, at evaporation plant'→'natural gas, liquefied, at freight ship'→'natural gas, liquefied, at liquefaction plant'→'natural gas, at production onshore'
8	6	2.35	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'transport, natural gas, pipeline, long distance'→'natural gas, burned in gas turbine, for compressor station'
9	7	2.31	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'transport, natural gas, pipeline, long distance'→'natural gas, burned in gas turbine, for compressor station'→'natural gas, at production onshore'
10	5	2.14	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural

			gas, at long-distance pipeline'⟶'natural gas, production DE, at long-distance pipeline'⟶'natural gas, at production onshore'
11	5	1.75	'natural gas, burned in combined cycle plant, best technology'⟶'natural gas, high pressure, at consumer'⟶'natural gas, at long-distance pipeline'⟶'natural gas, production GB, at long-distance pipeline'⟶'natural gas, at production offshore'
12	5	1.73	'natural gas, burned in combined cycle plant, best technology'⟶'natural gas, high pressure, at consumer'⟶'natural gas, at long-distance pipeline'⟶'natural gas, production RU, at long-distance pipeline'⟶'transport, natural gas, pipeline, long distance'
13	9	0.46	'natural gas, burned in combined cycle plant, best technology'⟶'natural gas, high pressure, at consumer'⟶'natural gas, at long-distance pipeline'⟶'natural gas, production DZ, at long-distance pipeline'⟶'natural gas, production DZ, at evaporation plant'⟶'natural gas, liquefied, at freight ship'⟶'natural gas, liquefied, at liquefaction plant'⟶'natural gas, burned in gas motor, for storage'⟶'natural gas, at production onshore'
14	8	0.45	'natural gas, burned in combined cycle plant, best technology'⟶'natural gas, high pressure, at consumer'⟶'natural gas, at long-distance pipeline'⟶'natural gas, production DZ, at long-distance pipeline'⟶'natural gas, production DZ, at evaporation plant'⟶'natural gas, liquefied, at freight ship'⟶'natural gas, liquefied, at liquefaction plant'⟶'natural gas, burned in gas motor, for storage'
15	4	0.34	'natural gas, burned in combined cycle plant, best technology'⟶'natural gas, high pressure, at consumer'⟶'transport, natural gas, pipeline, long distance'⟶'natural gas, burned in gas turbine, for compressor station'
16	7	0.31	'natural gas, burned in combined cycle plant, best technology'⟶'natural gas, high pressure, at consumer'⟶'natural gas, at long-distance pipeline'⟶'natural gas, production RU, at long-distance pipeline'⟶'natural gas, at production onshore'⟶'sweetening, natural gas'⟶'sour gas, burned in gas turbine, production'
17	7	0.26	'natural gas, burned in combined cycle plant, best technology'⟶'natural gas, high pressure, at consumer'⟶'natural gas, at long-distance pipeline'⟶'natural gas, production RU, at long-distance pipeline'⟶'natural gas, at production onshore'⟶'sweet gas, burned in gas turbine, production'⟶'sweet gas, burned in gas turbine, production'

18	6	0.23	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'→'sweetening, natural gas'
19	7	0.21	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NO, at long-distance pipeline'→'natural gas, at production offshore'→'sweet gas, burned in gas turbine, production'→'sweet gas, burned in gas turbine, production'
20	6	0.21	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'transport, natural gas, pipeline, long distance'→'natural gas, at production onshore'
21	2	0.20	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'
22	6	0.19	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production DZ, at long-distance pipeline'→'transport, natural gas, onshore pipeline, long distance'→'natural gas, burned in gas turbine, for compressor station'
23	7	0.18	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production DZ, at long-distance pipeline'→'transport, natural gas, onshore pipeline, long distance'→'natural gas, burned in gas turbine, for compressor station'→'natural gas, at production onshore'
24	6	0.18	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production RU, at long-distance pipeline'→'natural gas, at production onshore'→'well for exploration and production, onshore'
25	6	0.13	'natural gas, burned in combined cycle plant, best technology'→'natural gas, high pressure, at consumer'→'natural gas, at long-distance pipeline'→'natural gas, production NL, at long-distance pipeline'→'transport, natural gas, pipeline, long distance'→'natural gas, burned in gas turbine, for compressor station'

Coal			
1	2	22.29	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'
2	5	12.91	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
3	2	11.28	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'
4	2	4.99	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'
5	2	4.47	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'
6	2	3.63	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'
7	5	2.92	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
8	2	2.61	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'
9	2	2.27	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'
10	5	1.75	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
11	5	1.44	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
12	5	1.30	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
13	5	0.81	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
14	5	0.73	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
15	5	0.70	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
16	5	0.67	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'

17	5	0.61	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
18	2	0.60	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'
19	5	0.59	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
20	5	0.57	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
21	5	0.56	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
22	5	0.55	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
23	5	0.53	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
24	5	0.50	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'
25	5	0.46	'electricity, hard coal, at power plant'⟶'hard coal, burned in power plant'⟶'hard coal supply mix'⟶'hard coal, at regional storage'⟶'hard coal, at mine'

First Thesis Topic

This thesis topic is actually the second topic assigned. . In the first, the data required to perform the analysis required the assistance of industry players. Unfortunately this assistance was unavailable to me as a student, and the topic had to be abandoned. The following is the original thesis topic.

Norwegian University
of Science and Technology
NTNU

Department of Energy
and Process Engineering

EPT-M-2010-

MASTER THESIS

Stud.techn. Christine Hung

Spring 2010

Natural gas in materials production: Options for environmental improvement

Bruk av naturgass i materialproduksjon: vurdering av mulige miljøgevinster

Background and objective

Due to its high hydrogen to carbon ratio and clean-burning character, natural gas is commonly seen as a good way to reduce both climate and environmental impacts in energy applications. But natural gas can be used as a feedstock for petrochemical production and a reaction agent in metallurgical processes. It is to date uncertain how these two applications compare from an environmental perspective, especially with respect to the potential to reduce greenhouse gas emissions.

In metal production, coke is commonly used as a reducing agent for ores, turning the metal oxides into pure metals by producing carbon oxides. Hydrogen, however, can also serve as a reducing agent. The opportunity to capture CO_2 from the flue gas streams also depends on characteristics of the processes, most importantly the concentration of CO_2 in the gas stream and the total amount, but also the location with respect to potential reservoirs. Last but not least, costs and market conditions play important roles.

In the production of polymers, carbon as a feedstock becomes incorporated in the material, but fossil fuels also provide the energy the drives the reactions forward. Natural gas, oil, and coal are all common feedstocks, but biomass also offers an alternative.

Norway has a desire to utilize a larger fraction of its natural gas domestically to increase the domestic value added from this resource. The environmental consequences of such a policy are poorly understood. A life-cycle assessment approach is required to assess these questions.

The objective of this work is to develop and demonstrate a methodology for the comprehensive analysis of the environmental impact of using natural gas in petrochemical and metallurgical production processes in comparison to alternative applications of natural gas and alternative feedstocks.

From an environmental perspective, is it desirable to use natural gas for material production and coal for power production, or to use coal/coke for material production and natural gas for power production? What are the options, advantages, and disadvantages of capturing carbon dioxide in effluents?

For Norway specifically, is it desirable from an environmental perspective to export natural gas, or is it environmentally advantageous to use the natural gas for value creation through metalurgical and petrochemical industry domestically?

The following questions should be considered in the project work:

- What some promising options to use natural gas in materials production?
- Where is the state-of-art in the environmental impact of using natural gas as a feedstock to produce metals, polymers and other materials?
- What are alternative uses of natural gas?
- What are alternative ways of producing the materials at hand?
- What system configurations are desirable from an environmental point of view?

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Within 14 days of receiving the written text on the diploma thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

One – 1 complete original of the thesis shall be submitted to the authority that handed out the set subject. (A short summary including the author’s name and the title of the thesis should also be submitted, for use as reference in journals (max. 1 page with double spacing)).

Two – 2 – copies of the thesis shall be submitted to the Department. Upon request, additional copies shall be submitted directly to research advisors/companies. A CD-ROM (Word format or corresponding) containing the thesis, and including the short summary, must also be submitted to the Department of Energy and Process Engineering

Department of Energy and Process Engineering, 12. January 2010

Olav Bolland | Edgar Hertwich
Department Manager | Academic Supervisor

External Contact: Bjørn Utgård, Bellona