MSc Program
Environmental Technology & International Affairs

Linking Solar Energy with Waste Management: Photovoltaics vs. Biomass

The Case of Vienna

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, **RALUCA SANDULACHE**, hereby declare

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2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 15.06.2011

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Signature

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ABSTRACT

The primary objective of this study is to formulate a comparison between photovoltaic and biomass systems, as two renewable options capable of harvesting the energy in sunlight in order to contribute to addressing today's growing electricity demand. This assessment will integrate MFA techniques as a means to identify and examine the qualities and quantities of solid wastes that are produced from photovoltaic appliances and biomass combustion within a case study for the city of Vienna, Austria.

As a secondary aim, this paper attempts to evaluate the more advantageous technology in terms of resource efficiency and to offer a rough estimation as to the total material turnover involved in each of the selected systems.

The results indicate that for the production of one functional unit of electricity, biomass combustion is the less resource-efficient option, since it involves the use of a significantly higher amount of solid materials. Unless recycling is included, the quantities of waste produced by the biomass system show a threefold increase in relation to the photovoltaic. However, overburden taken into account, the photovoltaic alternative was found to produce an amount of waste double to that of biomass combustion. Calculations have proven that the total material being turned over by each system differ considerably.

1 Introduction

In a society that is becoming increasingly aware of the impacts of steeply growing resource use, sustainability assumes a paramount role in providing a feasible solution for global wellbeing. Meeting present society needs without compromising the safety of both future generations and the environment has been a target to achieve ever since the report of the Bruntland Commission more than two decades ago.

With regard to sustainability, it can be argued here that a basic focus needs to be placed on increasing resource efficiency and creating a shift from fossil fuels to renewable resources, through more consistent anthropogenic and geogenic flows.

Comprehensive data on the overall environmental impacts of renewable energy options has been mostly scarce until recently. However, new improvements in technology along with an almost unanimous global decision to exploit "green" energy - in the light of the recent rise in global warming, due inherently to fossil fuels combustion processes - prompted the need for more reliable information on the total amount of waste from renewable resources. Even given the growing interest in solar energy, guarantees regarding life-cycle sustainability are not always attainable. This constitutes a major reason for increasing data accessibility: the public should have access to enough data as to make an informed decision about the types of renewables that can undoubtedly constitute practical alternatives to traditional electricity production.

One of the most pressing concerns when it comes to "green" energy is directed towards the waste coming from the production process as well as waste materials connected to end-of-life cycles. This study is meant to provide a detailed analysis of the quantity and quality of wastes associated with photovoltaic and biomass systems, with a special focus on the solid wastes generated during the manufacturing stage.

As an instrumental part of the present paper, the author will first attempt to compare the two types of renewable resources in terms of final goods generated – in the form of electricity. The aforementioned parallel will be based on material flow analysis techniques. The goal of this methodology is to draw a comprehensive and transparent picture of the studied system, by considering all essential material flows driven by processes included within the system's boundaries.

Moreover, a first rough estimation of the total material turnover for both biomass and photovoltaic systems will be performed in a query to find out which of the two is the better alternative in terms of resource efficiency. This can only be achieved in the aftermath of analyzing and interpreting the overall results for the systems under scrutiny.

The paper introduces the common grounds in the relation between photovoltaics and biomass, followed by a description of solar energy principles and an insight into the sustainability issue, analyzed from a number of vantage points. An overview of the state-of-the-art technology will be provided in a second part of the study. The methodology section will begin with a theoretical review of the key terms and concepts in material flow accounting after which data acquisition will be considered and system boundaries, defined. In the following chapters, analysis of the systems for the Vienna case study will be undertaken and the analytic interpretation of the final empirical results will be completed by a "first rough assumption" in terms of total material turnover. A final section containing the summary and conclusions will be found at the end of the study, as will be a bibliography of the literature sources used for the present material.

1.1 Photovoltaics and Biomass: Common Ground

Based on the inexhaustible solar energy source, the two renewable technologies undertaken by this study – wooden biomass and photovoltaics – are starting to become more favoured by the public over conventional electricity production, since they are perceived as sustainable and environmentally-sound options.

Even though they operate in distinctly different ways, the two technologies investigated in the present paper essentially designate two processes capable of harvesting the energy in solar irradiation.

The upcoming sub-sections will provide detailed background information as to the principles of solar energy and to key terms connected to sustainability in dealing with renewable resources.

1.2 Principles of Solar Energy and Solar Irradiation

Solar radiation is undoubtedly a source for renewable energy, a source that has been employed successfully over the last years partly to create electricity with the use of both photovoltaic appliances and biomass combustion. Before detailing the state-of-the-art technology for PV and biomass systems, solar energy will be defined and its principles explained for the purpose of this paper.

Solar energy represents a by-product of nuclear fusion that is created when hydrogen atoms are fused into helium and then radiated into space as electromagnetic radiation. The total energy emitted from the Sun's surface amounts to approximately 63 Million Watts per square meter (W/m^2), out of which only a half of one billionth reaches the Earth due to the distance between the two and to the Earth's surface in comparison to the Sun. This amount of radiated electromagnetic energy emitted by the Sun is referred to as the solar constant and is carried by photons – particles with no mass that travel at the speed of light in a pattern similar to those of different wavelengths. Photons are able to release the energy produced at the core of the sun –primarily in the form of blue light when they come into contact with solar panels. This contact is the reason for the movement of electrons and furthermore, for the electricity generation.

An estimated 30% out of the approximately 1,368 Watts per square meter that are irradiated from the Sun is absorbed by the Earth's atmosphere, sea and clouds or reflected away from the Earth, leaving just an average of 1 kW per square meter that reaches the Earth's surface. The determination of the amount of energy that hits a specific point of the earth is made based on both the direct energy, the irradiance, measured perpendicularly to the ground, and indirect or diffuse insolation, measured horizontally (NASA Langley Research Center).

Figure 1 illustrates different solar irradiation levels depending on the region of the Earth, with the figures indicating the average annual energy available per square meter (expressed in kWh/m^2).

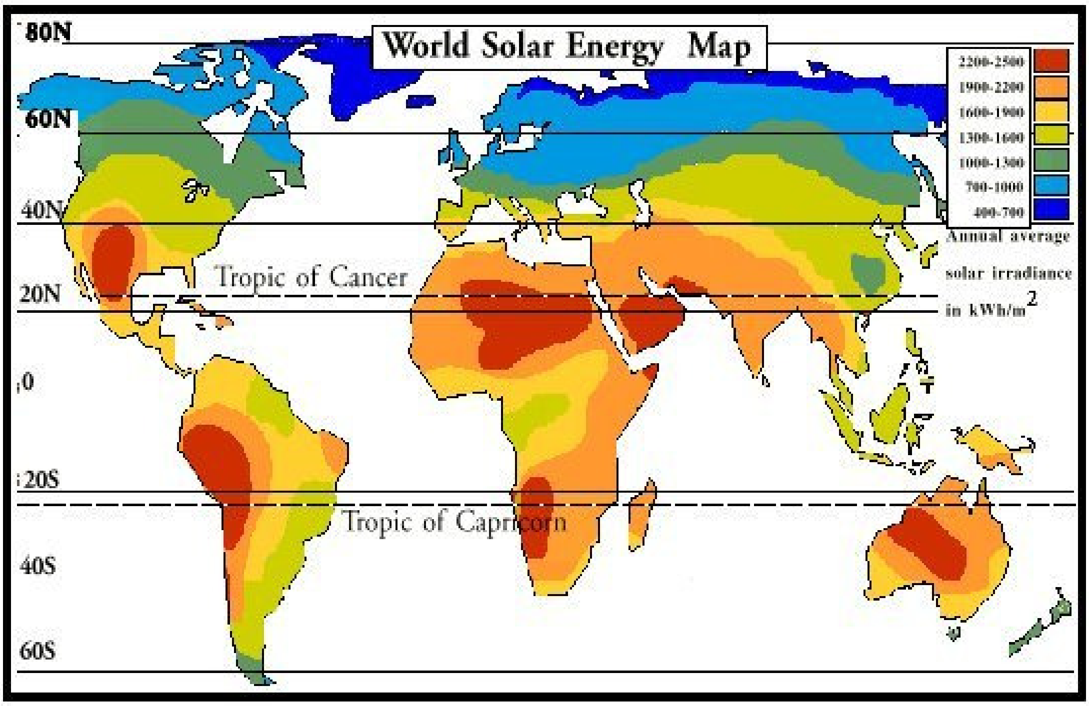

Figure 1 - World solar irradiance map (average annual energy in kWh/m^2)
Source: Solcomhouse.com – Solar power

Insolation levels at a specific location are directly dependent on multiple factors: season, weather patterns, altitude, time of the day and so on. These variables can account for significant differences in insolation intensity at any given time in various locations on the planet.

Available insolation in a specific area depends to a large extent on latitude, meaning that the closer to the equator a location is, the more sun it receives on an annual basis. Due to other factors mentioned above however, on areas with the same latitudinal coordinates different levels of solar irradiation can be measured.

1.3 Sustainability

As defined by the Bruntland Commission (1987), formally the World Commission on Environment and Development (WCED), a sustainable development stands for *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs.[...] It's a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are made consistent with future as well as present needs"*.

Since the use of finite energy resources – such as coal, oil and natural gas - to cover for the energy requirements of an increasing world population does not seem compatible with the theoretical meaning of sustainability, the coined term of "renewable energy" emerged as a solution considered to be in agreement with the concept of sustainable development.

Although clearly not under public scrutiny yet, renewable resources attempt to the integrity of the term "sustainability", as their use depends heavily on the use of non-renewable resources that have already started to become scarce.

Moreover, as demonstrated throughout this paper, renewables bear an undeniable ecological burden associated with the wastes and overburdens that are entrained/ carried along by the production of energy.

1.3.1 Energy Stability and Electricity Production

Advanced satellite technology can now be used to predict the amount of average insolation available in a target area, which can provide a fairly accurate image of the electricity to be produced by PV systems in different regions.

For Europe, for instance, the Renewable Energies Unit within the Joint Research Center of the European Union has computed, using the GRASS GIS software, a solar radiation database that provides "*monthly and yearly averages of global irradiation on horizontal and inclined surfaces, as well as climatic parameters needed for an assessment of the potential photovoltaic electricity generation*" (GEO - Group on Earth Observations, GIS – Geographical Information System Assessment of Solar Energy Resource in Europe, 2004). The system not only provides daily profiles of irradiance for a chosen time span and for selected climatic parameters, but can also supply estimates of solar electricity production.

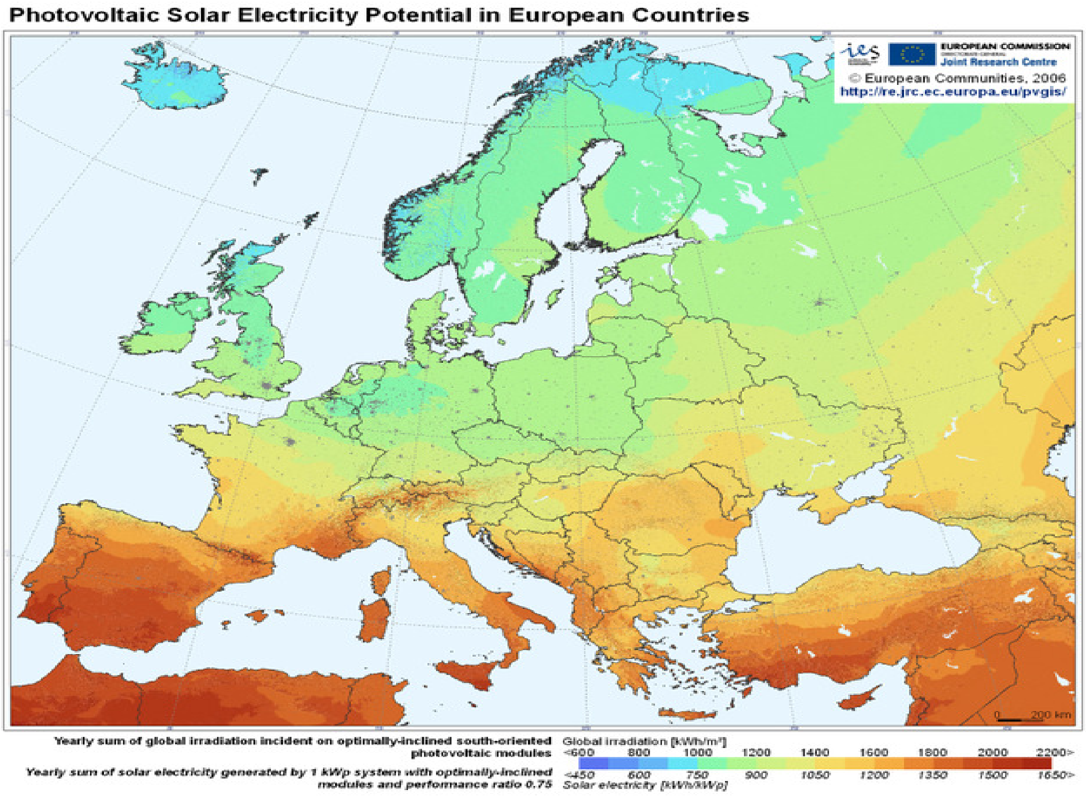

Figure 2 - Photovoltaic solar electricity potential for Europe
Source: Photovoltaic Geographical Information System (PVGIS)
Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology

The peak amount of electricity that can be generated by a particular photovoltaic installation in one year can be determined by applying the following formula:

$$kWhrs = \frac{yearly\ insolation\ level}{1000W} \times kWp \times m^2$$

Although PV modules are said to lose about 0.5% efficiency per year, relevant studies indicate current module design guarantees 90% power after 20 years of life and there is no visible evidence that degradation rate increases with time. (Dunlop et al., 2005)

1.3.2 Waste Management and Sustainability

With a total waste generation of 2.95 billion tonnes for EU-27[1] and a worldwide waste production steadily increasing mostly due to urbanization and GPD growth rates, environmentally and socially effective management waste strategies need to be perfected and applied at every step of the process.

While the objectives of waste management have followed a process of continuous transformation over time, the concept in itself integrates *"practices and treatment options comprising both prevention and collection strategies; separation steps for producing recyclables or for subsequent processing using biological, physical, chemical and thermal treatment technologies; and different landfill types"* (Brunner and Rechberger, 2004).

One of the essential purposes of waste management is to provide *"impulses for the material-oriented design of goods and processes, thereby permitting to take into account the possibilities of recovery and environmental protection already at the levels of production and supply"* (Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2006).

As sustainability in waste management dominates decision-making today, a waste hierarchy has emerged to ensure that this key factor is taken into account. Therefore, strategies that include reduction and prevention of waste arising, reusability of waste and energy recovery should be considered before landfill disposal – landfilling is considered the lowest environmental priority option in terms of treating and disposing the waste and should therefore be examined only as the last resort.

In order to properly handle the waste that is generated in an economy, an overall analysis of the sources and paths of substance and material flows needs to be performed, as this allows decision-makers to differentiate between effective and less effective

[1] Total waste generation calculated for 2006 by the Institute for European Environmental Policy

measures depending on the type of waste and to ensure economically viable solutions are adopted to fit the context of the national economy as a whole.

Chanchampee and Rotter (2007) emphasize the role of Material Flow Analysis as a decision support tool for waste management systems in growing economies, due to the fact that this method has proven reliable in terms of estimating substitution potentials for primary raw materials and, at the same time, the demand for treatment and logistical capacity when it comes to effective waste management.

1.3.3 Resource Efficiency and GDP

Resource efficiency is defined as the ratio of gross domestic product (GDP) to domestic material consumption (DMC) and indicates the economic achievement gained, in Euro per ton material deployment.

As the European Commission COM(2011) 21 indicates in their “Flagship initiative under the EUROPE 2020 Strategy”, the EU has a priority to increase resource efficiency as to “*develop new products and services and find new ways to reduce inputs, minimise waste, improve management of resource stocks, change consumption patterns, optimise production processes, management and business methods, and improve logistics*”.

In accordance with their latest report for Austria, the International Energy Agency argues that the country of nearly 8.4 million inhabitants is one of only five states in the EU that has already reached the 2020 targets, which refer to a minimum of 20% of their primary energy supply being covered from renewables. The use of these renewable energy resources is considerable relative to other EU member states, with renewables accounting for 21.3% of the total primary energy supply (TPES) in 2005 (IEA, 2008).

Although the country’s resource efficiency increased considerably between 1995 and 2008, with 1.54 million Euro per ton material deployment in 2008, as compared to only

1.32 million Euro in 1995, Statistik Austria argues that the results should be regarded as provisional, especially since it was found that the reported quantities of mineral raw materials appeared to be underestimated.

This is why practices consistent with Austria's goal to highly improve resource efficiency are currently a priority. If the two renewable alternatives examined in this study appear not to be as resource efficient as expected, further research should be performed in order to investigate if any steps for improvement are to be taken.

2 Overview of the State-of-the-art Technologies

2.1 Photovoltaic Systems

Photovoltaic (PV) systems can significantly contribute to the creation of a sustainable energy mix, since they are able to convert sunlight directly into electricity. Photovoltaic cells are basically semiconductor devices that produce energy once solar radiation falls on them.

The basic components needed in a photovoltaic system can be divided into three main categories: a) structure and installation, b) power conditioning and control system and c) storage batteries. The first category will typically include the photovoltaic panel, the comparator, the mechanical part and the design structure. The microcontroller, the printed circuit board (PCB), relay and wiring are considered to be part of the power conditioning and control system. The component of the last category is used to store the converted solar energy gained from the photovoltaic system (Yaik, 2007). The balance of system (BOS) accounts for everything else in a PV system except the PV module.

Today most PV modules produced are silicon-based although other semiconductor materials that are taken as compounds, like the combination of Cadmium and Tellurium or that of Gallium and Arsenic, are expected to surpass the silicon-based PV market within the next 15-20 years.

Photovoltaic modules are rated depending on their current-voltage (I-V) characteristics measured at standard reporting conditions (SRC). The average effective efficiency, which is derived from module energy out divided by solar energy in calculations averaged on a weekly basis, is then analyzed and compared with module current-voltage measurements performed at SCR (del Cueto, 2001).

The following subsection will review types of technologies available for the production of monocrystalline/ single crystalline silicon PV modules.

2.1.1 Crystalline materials

Monocrystalline (mono-Si)/ Single Crystalline (sc-Si) Silicon

The technology behind this kind of PV cell comprises single crystal silicon seeds produced from high-purity polycrystalline that is melted in quartz crucible using the Czochralski process. Figure 3 shows the most common method of growing crystals for the development of wafers, known as the Czochralski method. The material used for this process is electronic grade silicon (EG-Si) with 99.99% purity, that is refined from metallurgical grade silicon (MG-Si).

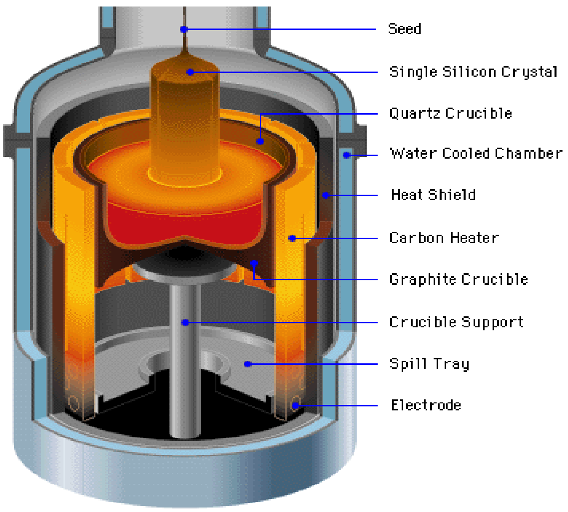

Figure 3 - Czochralski process Source: Jones, 2001

Single crystal ingots are formed by dipping the seeds into a molten mass of polycrystalline and are then sawed into thin wafers - typically 200-400 micrometers - that follow a process of polishing, doping, coating, interconnecting before being finally assembled into modules and arrays (Mah,1998). During crystal-growing, dopants like phosphorous or boron are added to *"increase the concentration for mobile carriers"*, which in turn increases the conductivity of the device (Jones, 2001).

A substitute to the Czochralski method of crystal growing is the float zone technique. During the course of this process – displayed in Figure 4 - a single crystal is pulled from a molten zone of highly-purified polycrystalline silicon, which is previously required to pass an induction heating procedure. The material produced by the float zone technique bears exceptional purity and has a very low oxygen contamination, as opposed to the Czochralski material that makes use of the quartz crucible and where oxygen contamination cannot be avoided (Goetzberger et al. ,2002). In terms of price, the high purity of the float zone material yields a more expensive manufacturing cost in an industry where price is of overriding importance.

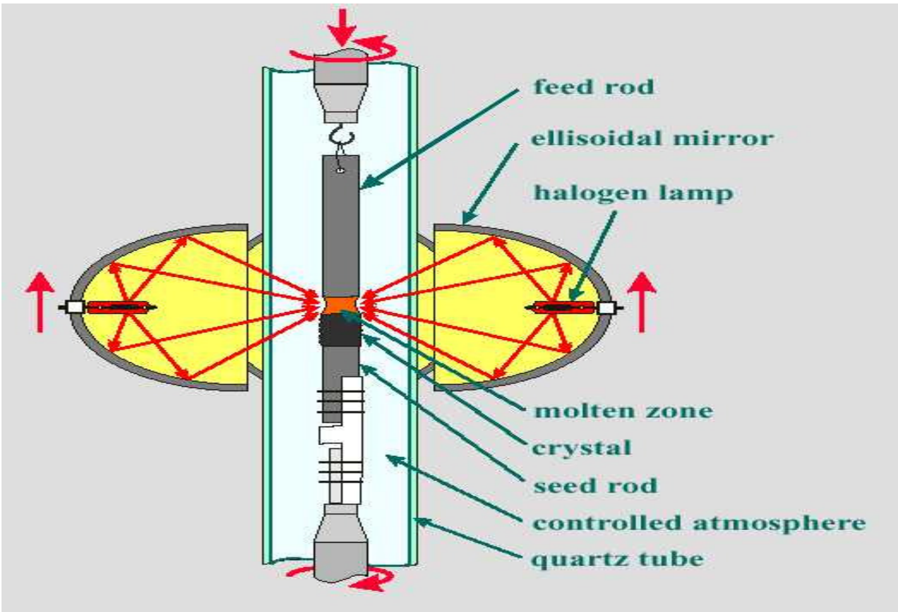

Figure 4 - Floating zone technique Source: Jones, 2001

One reason why single crystal silicon cells are widely produced in the PV industry is the fact that their uniform crystal lattice structure, with practically zero defects or impurities, translates into a higher energy conversion efficiency-between 14-20% - as compared to noncrystalline materials, for example. As a downside, due to the thickness requirement of the ingots, a high amount of raw silicon is needed, with a significant part being lost in the wafering process.

2.2 Biomass Systems

Electricity generation from biomass augmented by a factor of 4.7 from 1990 to 2005 with an average rate of approximately 11% per year, placing biomass in the top two renewable energy sources in the European Union (Obernberger and Thek, 2008). Figure 5 shows the share of electricity from biomass sources in the EU member states. Since the second major share of this increase is attributable to Combined Heat and Power (CHP) plants based on biomass combustion (Kautto and Jaeger-Waldau, 2007), it is this type of technology that will be chosen for comparison to the photovoltaic system in this case study. From a power capacity point of view, several options are available in terms of technology for centralized biomass combustion.

For CHP plants with nominal electric capacity of up to 150 kW the most suitable up-to-date technology is based on the application of the Stirling engine (Obernberger at al, 2003). While considered to be a breakthrough for small-scale plants that use solid biomass as fuel, the Stirling engine is expected to be available on the market within the next few years, provided that prototype plants that are in operation since 2005 demonstrate their reliability.

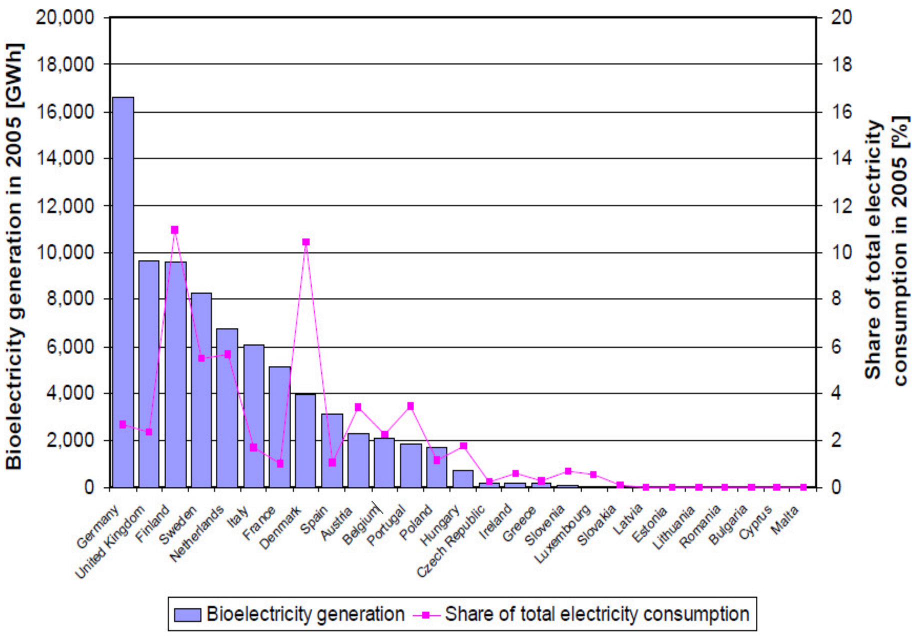

Figure 5 - Electricity generation from biomass in EU-27
Source: Obernberger and Thek, 2008

Highly efficient applicable technologies for combined heat and power plants targeting in the medium-scale power range consist of either a steam engine, a steam turbine or an Organic Rankine Cycle (ORC). The latter process, that operates as an entirely closed unit utilising silicon oil as working medium, has proven its technological maturity and has been used successfully during the last years.

In terms of biomass-fired plants CHP plants with a larger nominal electric capacity than 2000 kW the steam turbine process is to be considered the single most significant market-proven technology. After having achieved a high level of development for many years, processes involving steam piston engines and steam turbines now represent state-of-the art for solid biomass combustion (Obernberger and Thek, 2008).

The following section will describe and analyze in more detail the CHP technology for centralised applications of biomass combustion which makes use of the steam turbine process, as this technology will be relevant for the case study investigated in the present paper.

Steam Turbine Process for Large Scale Combustion Plants

The CHP technology that relies on a steam turbine process represents a field-tested large-scale application (>2 MW_{el}) in the terms of electricity production from solid biomass.

Aside from the steam turbine that is connected to an electric generator, incorporation of the following components is paramount for cogeneration plant with a power capacity of more than 2MW: a firing subsystem to ensure an efficient combustion of solid biomass, a steam subsystem containing a boiler and steam delivery unit together with an added feed water and condensate system.

In terms of turbine technology, two types of turbines are currently available on the market: backpressure turbines on the one hand and, extraction condensing turbines, on the other. While projects with all year round demand for heat in form of hot water and low pressure steam make use of backpressure turbines, plants that need uncoupling of the heat production and electricity commonly employ extraction condensing units in order to increase the electricity production efficiency by directing the steam that would normally go towards heat supply in the low pressure unit of the turbine.

Table 1 - Steam parameters and electric capacities for steam turbine processes
Source: BIOS Bioenergiesysteme GmbH

Parameter	**Value**
Live steam temperature	450 – 540 °C [2]
Live steam pressure	20 – 100 bar(a)
Live steam flow rate	10 – 125 t/h
Back pressure or extraction steam pressure	1 – 10 bar
Exhaust steam pressure	0,05 – 0,60 bar(a)
Electric capacity	2 – 25 MW_{el}
Electric annual use efficiency ([2])	18 – 30 %

Pertinent technical data for steam turbine processes are depicted in Table 1, with the observation that the information is only valid for CHP plants with a capacity range between 2 and 25 MW_{el}.

Facilities whose power ranges reach more than 5 MW_{el}, often utilize water tube boilers to produce steam in order to attain the desired live steam parameters, while smaller-scale facilities have the option to make use of either water tube boilers or still fire tube boilers.

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[2] Depending on the type of biomass used as fuel, live steam temperatures range between 450 – 540°C. For instance, in case of waste wood, live steam temperatures should be kept constant around 450°C to prevent unusually high deposition and corrosion damage. When using chemically untreated wood-like biomass, temperatures can safely reach 540°C.

The working principle of this state-of-the-art technology available for combined-heat-and-power production plants with a nominal electric capacity of over 2 MW is based on the classical Clausius-Rankine-Process, in which high pressure and high temperature steam is produced in a water tube boiler before entering the steam turbine. As conversion from thermal energy to mechanical work occurs in this step of the process, low pressure steam from the turbine passes to a condenser shell, which generates a condensate that is transferred back into the boiler by the boiler feed-water system in order to complete another cycle (BIOS Bioenergiesysteme GmbH).

It should be noted here that, having reviewed the most important aspects related to cogeneration plants the basis is now complete for the introduction of the plant selected for comparison against the photovoltaic system. Details on the CHP plant used in this paper's case study will be discussed under chapter 5.

3 Methodology and Data Selection

3.1 Material Flow Accounting – Material Flow Analysis

In order to answer the research questions posed above, a way of measuring all important good and substance flows, in terms of both quantity and quality, for the photovoltaic and biomass systems is a prerequisite for performing a comprehensive assessment of the system as a whole. To that purpose, material flow accounting can be classified as a recurring and cost-efficient technique to all materials and substances employed in the production of a specific product, in this case, the production of electricity from two renewable sources: biomass and solar energy.

Material accounting has been widely used on national and regional levels in order to identify the essential flows and stocks that take place between the environment and the economy, and in that sense provide a comprehensive base for informed decision-making in terms of national or regional planning and strategies – e.g. exploitation and allocation of resources, resource-scarcity forecasting, pollution treatment and prevention, nutrient control, waste-treatment facilities planning and design.

The base for material accounting and the paramount methodology to be employed in this thesis is material flow analysis that, as conceptualized by Brunner and Rechberger (2004), encompasses *"a systematic assessment of the flows and stocks of materials within a system defined in place and time. It connects the sources, the pathways, and the intermediate and final sinks of a material. Because of the law of the conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs, stocks, and outputs of a process"*.

In a basic metabolic system, raw (crude) materials, water and air are extracted from the natural ecosystem as inputs and follow a series of processes before being transubstantiated into products and finally transferred to the natural system once again, this time as outputs – solid waste and emissions to air and water.

The MFA methodology provides a tool for measurement and assessment of the metabolic performance of a system with respect to sustainable development, since an MFA-based on total material balance can specifically identify the flows and processes that have the most potential for improvement (Brunner and Rechberger, 2004).

The application of material flow analysis to any designated system involves clearly identifiable temporal and spatial limits or borders, also known as the system boundaries that are meant to enclose a set of processes, stocks and material flows. For the understanding of the system, the following fundamental terms need to be defined: materials-comprising of goods and substances, processes, stocks, flows/fluxes.

The concept of "material" denotes both substances and goods. "Substances" indicate types of matter with constant chemical composition that comprise of uniform units – atom units account for the creation of elements, while units on a molecular level lead to the formation of chemical compounds.

The distinction between goods and substances can be made by assigning economic values to substances; "goods" bear either positive (e.g. natural gas) or negative (e.g. waste) values, according to Brunner and Rechberger (2004), who also define the term "process" as "*transport, transformation, or storage of materials*". The categorization of the latter-mentioned concept can be done based on the generating factor – thus the differentiation between geogenic and anthropogenic processes.

Materials stored within a process are conventionally identified as "stocks" that are attached a physical unit. One of their characteristic consists of the fact that they can remain constant, or change their mass value, by accumulating or depleting materials.

Lastly, under the MFA convention, links between processes are labelled as flows – mass per time units, or fluxes – mass per time and cross section units.

3.1.1 Software Tool – STAN

In order to perform graphical representations of the two systems considered in this study in a manner that is consistent with the material flow analysis terminology and procedures, the author chose STAN – short for SubSTance flow ANalysis, a software tool that complies with the Austrian standard ÖNorm S 2096 and is appropriate for application in waste management.

3.2 Life Cycle analysis - Life Cycle Inventory

Life cycle inventory is recognized as a "cradle-to-grave" analysis of a product's life, therefore identified as being able to discuss the environmental impact for all stages involved, including raw material extraction through processing, manufacture, distribution, transportation that links all the steps, utilization and maintenance, and finally recycling or disposal.

Life cycle analysis (LCA) data distinguish between two categories: the environmental input-output data (EIO), obtained by carrying out national or economy-wide inventories, on the one hand, and unit process data, on the other hand. The EIO method, which stands for Economic Input-Output, is designed to estimate all the flows resulting from activities in a certain economy (Carnegie Mellon University, 2008). By comparison, the unit process data stem from actual measurements or direct inquiries of companies or plants handling the manufacturing of the product of interest.

3.3 Data Acquisition

For the purposes of this study, sources to contribute to data acquisition have been obtained in various ways. A large part of the data relevant for photovoltaic systems was obtained based on literature review and selection. Complementary information was gathered from the GEMIS database, whose details can be found in the next section. The EcoInvent database constituted a third source for data gain.

Concerning the biomass system, data in a significant share were acquired due to personal consultation with the Vienna Simmering staff and public information from the official webpage of the plant. Missing data, mostly in terms of expenditures for creation, were found using the aforementioned GEMIS database.

3.3.1 GEMIS Software

GEMIS stands for "Global Emission Model for Integrated Systems", and comprises a LCA software and database for energy, material and transport systems. Since version 3.0 appeared in 1996, GEMIS has been available as a public domain software. The standard project database which is also freely accessible for public contains information on raw and base materials, processes for electricity and heat production, fossil and renewable fuels etc. In its calculation of impacts GEMIS includes the total life-cycle of materials in process chains and covers for each process the emissions, liquid and air pollutants, solid wastes and land use, provided the data are available in the database.

3.4 System Boundaries

The primary question that will be attempted to be answered in this paper is whether photovoltaics (PV) and biomass combustion are, besides renewable energy sources, also sustainable technologies in terms of waste management. Based on the amounts of solid waste generated by each technology, resource efficiency and total material turnover will be also assessed in accordance to the results yielded by the material flow analysis for the two systems.

Since the present paper is meant to first identify and then quantify, and assess all solid material flows that enter the systems under discussion, distinct boundaries will be determined from the outset as to allow for differentiation between the systems that are undergoing study and anthroposphere. Precise quantification of solid material inputs require precise drawing of the borderline to nature, which will be covered in the upcoming section. Because of requirements of the system boundaries selected for this work virtual production waste (VPW) and virtual overburden (VOB) will be defined here.

Overburden designates geologically the material *"of any nature, consolidated or unconsolidated"*, overlying a useful mineral deposit (Hacettepe University Department of Mining Engineering, U.S. Bureau of Mines, 1996). Overburden is also referred to as "waste" or "spoil" and is usually removed during surface mining (Kogel, 2006). In this study, the overburden will be quantified depending on the amounts of extracted materials that are needed for the production supply.

Also referred to as embodied waste, overburden comprises the waste and overburden resulting from an entire product lifecycle. This is an accounting methodology whose aim is to quantify the total waste and overburden involved in the production of a good or for the provision of a service.

For the purposes of the present study, such waste and overburden will be referred to as "virtual" in order to draw attention to the fact that processes generating them are placed outside of the system boundaries. Nevertheless, they will be taken into consideration as to aid to a more accurate depiction in terms of total solid material being turned over by the two systems.

The following subsections describe system boundaries that apply specifically for chapters four and five of this paper. It should be noted that for the results section different system boundaries will be selected and detailed throughout the respective chapter.

3.4.1 System Boundaries for Photovoltaic System

The spatial system boundary adopted for photovoltaics designates the average private household in Vienna, while the temporal boundary will be chosen to have a 30-year time frame as to serve for consistency with the assumed lifetime for one PV module.

In regard to the application type, a grid-connected photovoltaic system, with modules installed in-roof will be selected. The functional unit used for calculations is 4,417 kWh representing the mean yearly electricity consumption for one household.

Further explanations and details can be found in chapter four of this study.

3.4.2 System Boundaries for Centralized Biomass Combustion

The spatial system boundary selected for this second renewable option under consideration was selected to be a biomass-fueled cogeneration plant in Vienna, as only centralized biomass combustion will be undertaken by this study. For the temporal boundary, a 30-year time frame will be set as to reflect the whole lifetime of the plant.

Additional aspects on technical data of the CHP plant and system boundary analysis are to be covered throughout chapter five.

4 System analysis – Photovoltaics

4.1 Overview

As a result of significant investments towards solar infrastructure expansion, the solar industry has extended its small market share while showing signs of greater potential. Although aiming towards a viable source of renewable energy, the photovoltaic industry is currently faced with two essential dilemmas: how to ensure a manufacturing process with as small as possible production waste and how to dispose of panels after their useful lifetime (Nath, 2010).

This section will determine, on the basis of MFA techniques, the main material flows within photovoltaic systems as well as provide a qualitative and quantitative assessment of the waste products created during each of the stages leading to the production of solar panels, with a special focus on the manufacturing process.

Data collection as well as any uncertainty values will make the topic of discussion throughout the present chapter. In order to create a transparent, facilely interpretable system that will undergo investigation in the results section, the data input for photovoltaics was assembled as a cross-reference of literature studies, based on life cycle inventories of photovoltaics, with the GEMIS database.

As mentioned in the methodology section, the spatial system boundaries for the monocrystaline/ single crystalline silicon technology is a household in Vienna, while the temporal boundaries cover an assumed 30- year lifetime of PV modules, based on the work of de Wild-Scholten and Alsema, 2005 . The Viennese household whose average yearly electricity consumption is of 4,417 kWh[3] will serve as the functional unit for this study's purposes.

[3] This unit is consistent with the Statistik Austria (2009) report – "Average electricity consumption of households 2008 by categories of consumption"

Table 2 depicts the main relevant assumptions for the PV system under study, with the right column containing the source of the information.

Table 2 – Assumptions for the PV system under study

	Value	Source, comment
Average yearly consumption of a household	4417 kWh/a	Statistik Austria, 2009
Mean yearly global irradiation (at optimal angle)	1300 kWh/m²a	PVGIS, 2010
Monocrystalline module efficiency (excl. frame)	14%	Alsema et al., 2005
Module area needed	24.27 m²	own calculations
Area of one module (excl. frame)	1.25 m²	Alsema et al., 2005
Modules needed for a household	19.42 pcs	own calculations
Modules needed rounded	20 pcs	

The module efficiency without frame for the monocrystaline/ single crystalline silicon is assumed to be 14%, based on actual measurements from different PV producer companies (Alsema & de Wild-Scholten, 2005), while the lifetime of one module is taken as 30 years. In order for the module to yield the aforementioned efficiency proportionally to the annual electricity consumption for a household, the amount of total solar energy required to be reflected on the panel is calculated as the yearly household consumption divided by the module efficiency.

Since this study's main focus is on Vienna, mean yearly global irradiation for this geographical location was found to be 1,140 kWh/m^2 on horizontal plane and 1,300 kWh/m^2 on a plane at optimal angle. The latter value will be assumed for the calculations, noting that the optimal angle corresponds to 35° when facing south.

Again, calculations have been performed to reveal the module area in m^2 needed for a household with the mean yearly electricity consumption considered for this study. The total module surface is obtained by dividing the total solar energy demand by the mean yearly global irradiation on a plane at optimal angle.

While the cell area of one module is taken as being 1.12 m^2 and the area required for one module accounts for 1.25 m^2, 20 is rounded off as the number of PV modules to be installed on a household that uses no grid-electricity for its energy supply.

4.2 Waste Products Identification and Quantification

All the solid material flows needed within the module manufacturing process have been identified using life cycle inventory (LCI) methods, while the quantification of waste products and overburden has been performed based on the GEMIS database in addition to the LCI studies.

In order to meet the demands of the task in hand, the following three sources for life cycle inventory are applied to this paper to ensure a fairly comprehensive data collection: "*Environmental life cycle inventory of crystalline silicon module production"* (Alsema & de Wild Scholten, 2005), EcoInvent Photovoltaics (Swiss Centre for Life Cycle Inventories, 2009) and GEMIS database.

The data have been aggregated into multiple stages that will be described precisely in the upcoming sub-section.

For the PV manufacturing phase, structuring of the data into five sub-processes has been undertaken, four of which are in accordance with the LCI performed by Alsema and de Wild-Scholten, 2005: 1) polycrystalline silicon production from metallurgical grade silicon (MG-silicon), 2) crystallization and wafering, 3) cell processing and lastly, 4) module assembly. We assume here the production of the inverter and PV mounting system as an additional sub-process under the above-mentioned process.

The following sub-sections comprise a more detailed description of the solid material flows, wastes and overburden for the discerned stages mentioned above. Based on data collection, the material requirements are calculated per functional unit – one household with a mean annual electricity consumption of 4417 kWh.

4.3 Virtual Production Waste and Virtual Overburden for PV Manufacturing Plant

Literature data on expenditures for creation in case of PV manufacturing facilities were found to be scarce. Nevertheless, construction materials expended for the creation of a solar cell factory with state-of-the-art technology were available in the EcoInvent study on photovoltaics from 2009.

The relevant data were imported from Ecoinvent and adapted to this study's purposes. Calculations to upscale the infrastructure materials to the requirements of the present system boundaries have been performed, having as basis the raw materials needed for a 25-year lifetime. The results of the computations are available in Table 3, additional to the requirements calculated for a single household.

Data for the other sub-processes involving polycrystalline silicon production, crystallization and wafering, module assembly, and inverter and mounting system were not available. Subsequently, the materials found to cover for the infrastructure of the PV cell production were multiplied by the number of sub-processes (5x) assumed to be within the "PV manufacturing" process – the name designated for this process in the MFA diagram. This assumption offered a more reliable amount in terms of infrastructural materials for this study's purposes, but further research would be desirable (Tables 3 and 4).

Table 3 – Expenditures for creation of solar cell factory
Source: own calculations using data from EcoInvent 2009

	Demand for lifetime (25years)	Demand for 30 years	Demand for 1 HH in 30 years
Steel reinforced	1.90E+05	2.28E+05	1.84E+00
Steel low-alloy	1.10E+05	1.32E+05	1.07E+00
Brick	5.06E+02	6.07E+02	4.91E-03
Concrete	4.32E+06	5.18E+06	4.19E+01
Metal working machine	1.00E+04	1.20E+04	9.71E-02
sum:			**45**

The next step consisted of researching the GEMIS database for virtual production waste and virtual overburden for the newly ascertained material requirements. The third and the fourth column in Table 4 represent the VPW and VOB adapted in terms of kg per kg of material expended. The fifth and sixth column from the left show the amounts needed for the photovoltaic system investigated in this paper.

Table 4 – Virtual production waste and virtual overburden of solar cell factory
Source: own calculations using GEMIS 4.6 database

PV module manufacturing infrastructure	**Selected processes in Gemis**	**Virtual production waste & virtual overburden**			
		VPW kg/kg material	**VOB kg/kg material**	**VPW per HH kg**	**VOB per HH kg**
Steel reinforced	metal\ steel-mix-DE-2010	3.8E-01	2.4E+00	7.10E-01	4.47E+00
Steel low-alloy	metal\ steel-mix-DE-2010	3.8E-01	2.4E+00	4.11E-01	2.59E+00
Brick	nonmetallic minerals\ clay bricks	1.4E-04	3.1E-01	6.94E-07	1.52E-03
Concrete	nonmetallic minerals\ concrete-DE-2010	2.0E-04	4.5E-01	8.29E-03	1.87E+01
Metal working machine	metal\ steel-mix-DE-2010	3.8E-01	2.4E+00	3.74E-02	2.35E-01
Sum:				**1.17**	**26.00**

4.4 Virtual Production Waste and Virtual Overburden of PV Module Material Supply

Material requirements for the production of the monocrystalline/ single crystalline PV modules are depicted in Table 5, with the right-hand column indicating the manufacturing sub-processes that the mentioned materials are attributable to. These have been computed for the annual electricity consumption per household by multiplying the quantities employed in the manufacturing of one module by the number of modules needed to support the electricity requirement of a household. The next step comprised division by 30 years to calculate the yearly demand of these materials for the average private household.

Table 5 – Materials required for PV module manufacturing
Source: own calculations using data from Alsema et al. (2005)

PV module material supply	Demand for one module (kg)	Demand for one HH (kg)	Manufacturing step
MG-silicon	2.17E+00	4.33E+01	1
Quartz crucible	4.37E-01	8.74E+00	2
Glass	1.21E-02	2.43E-01	2
Steel wire	1.81E+00	3.62E+01	2
Silicon carbide (SiC)	3.17E+00	6.34E+01	2
Phosphorus paste	1.67E-03	3.33E-02	3
Metallisation paste	8.59E-02	1.72E+00	3
Polystyrene, expandable	4.67E-04	9.34E-03	3
Aluminium profile	3.80E+00	7.60E+01	4
Polyphenylenoxid	2.00E-01	4.00E+00	4
Glass sheet	1.14E+01	2.28E+02	4
Ethylen vinyl acetate	1.30E+00	2.60E+01	4
Back foil	3.20E-01	6.40E+00	4
Copper	1.40E-01	2.80E+00	4
Tin	7.00E-03	1.40E-01	4
Lead	4.00E-03	8.00E-02	4
Nickel	2.00E-04	4.00E-03	4
Soldering flux	1.00E-02	2.00E-01	4
Silicone	2.90E-03	5.80E-02	4
Silicone kit	1.50E-01	3.00E+00	4
Cardboard	1.37E+00	2.74E+01	4
Sum:	**26.38**	**527.69**	

For the newly ascertained amounts of materials, calculations have been performed to determine the quantity of virtual production waste and virtual overburden that is created by raw material extraction and processing (Table 6). The amounts corresponding to tin, soldering flux, silicone, and silicone kit were not available. Consequently, for these materials VPW and VOB will not be considered further.

Table 6 – Virtual production waste and virtual overburden of PV module material supply
Source: own calculations using GEMIS 4.6 database

PV module material supply	Selected processes in GEMIS	Virtual production waste & virtual overburden			
		VPW kg/kg material	VOB kg/kg material	VPW per HH kg	VOB per HH kg
MG-silicon	Fabrication\ silicon-MG-DE-2010	6.9E-02	4.2E+01	3.0E+00	1.8E+03
Quartz crucible	Xtra-quarrying\ quarz sand-DE-2000	1.3E-04	1.5E-01	1.1E-03	1.3E+00
Glass	nonmetallic minerals\ glass-flat-DE-2000	1.4E-02	6.7E-01	3.4E-03	1.6E-01
Glass sheet	nonmetallic minerals\ glass-flat-DE-2000	1.4E-02	6.7E-01	3.2E+00	1.5E+02
Steel wire	metal\ steel-mix-DE-2010	3.8E-01	2.4E+00	1.4E+01	8.8E+01
Silicon carbide (SiC)	chem-inorg\ silicon carbide	6.8E-02	1.2E+00	4.3E+00	7.4E+01
Phosphorus paste	chem-inorg\ phosphorus paste	5.2E+01	1.8E+00	1.7E+00	6.0E-02
Metallisation paste	chem-inorg\ metallisation paste	2.7E-05	1.0E+00	4.6E-05	1.7E+00
Polystyrene, expandable	chem-org\ PS-DE-2010	4.3E-03	1.6E+00	4.0E-05	1.5E-02
Aluminium profile	metal\ aluminium-DE-2010	1.2E+00	5.1E+01	8.8E+01	3.9E+03
Polyphenylenoxid	chem-org\ polyphenylenoxide	2.1E-02	6.2E+00	8.4E-02	2.5E+01
Ethylen Vinyl Acetate	chem-org\ EVA	1.5E-02	2.7E-01	3.9E-01	6.9E+00
Back foil	chem-org\ back foil for PV-modules-DE-2005	1.3E-02	1.7E+00	8.2E-02	1.1E+01
Copper	meta\ copper-DE-mix-2010	2.9E+01	5.9E+01	8.1E+01	1.7E+02
Lead	metal\ lead-DE-mix-2010	3.1E-03	2.8E+00	2.5E-04	2.2E-01
Nickel	metal\ nickel-DE--2010	5.7E+01	1.1E+02	2.3E-01	4.5E-01
Cardboard	pupl-paper\ kraft liner-EU	3.0E-02	2.3E+00	8.2E-01	6.2E+01
Tin	n/a	n/a	n/a	n/a	n/a
Soldering flux	n/a	n/a	n/a	n/a	n/a
Silicone kit	n/a	n/a	n/a	n/a	n/a
Silicone	n/a	n/a	n/a	n/a	n/a
Sum:				**196.71**	**6332.97**

4.5 Solid Wastes from PV Manufacturing

In coordination with Table 7, five sub-processes are clearly identifiable within the main PV manufacturing process. The production of the solar module itself implies outputs referred to as PV module manufacturing wastes from each of the sub-processes.

These amounts of manufacturing waste are presented and quantified in Table 7. The same calculation method as for the PV module material supply was applied here in order to measure the amounts necessary for one and consequently, 20 modules – the number needed to support a household's electricity consumption per year.

Table 7 – Solid wastes from PV manufacturing
Source: own calculations using data from Alsema et al. (2005)

Solid wastes from PV manufacturing		Corresponding waste per	
		module (kg)	household (kg)
Step 1	MG-silicon waste	0.25	4.99
Step 2	Silicon waste	0.49	9.71
	Cutting waste	7.28	145.65
Step 3	Photovoltaic cell waste	0.32	6.33
Step 4	Solar cell waste	0.02	0.30
	Solar glass	0.11	2.20
	Ethylvinylacetate foil	0.05	1.00
	Back foil	0.02	0.40
Step 5	n/a	n/a	n/a

For the production of 1 kg of high-purity polycrystalline silicon, the necessary amount of metallurgical grade silicon (MG-silicon) is 1.13 kg. The assumption here is that the rest of 0.13 kg goes to waste. The share of MG-silicon in the production of one module is also shown in Table 7.

For the manufacturing of inverters and mounting systems – assumed as step five in the production process – no solid nor liquid wastes were found to be available. Therefore, the possible waste products coming from manufacturing were not considered in the calculations.

4.6 Solid Wastes during PV Module Operation and Maintenance

During standard performance, photovoltaic modules do not generate any kind of waste, in addition to being emission and noise-free (EcoInvent, 2009). Possible waste materials produced as a result of maintenance operations are neglected in this study.

4.7 Solid Wastes from PV Module Disposal

The assumption that after their useful life the modules are disposed of as solid wastes yields a total amount of 435.3 kg in dismantling materials. Shown in Table 8 are the PV module materials and their total sum in kg directed towards disposal facilities after 30 years.

The lifetime of the inverter was assumed to be 30 years, based on literature (Fthenakis et al, 2009), while the life expectancy of the mounting system was averaged to 60 years. The peak power of the chosen inverter was 2500 W, which needed up-scaling to 3300W, since the peak power of a module was found out to be 165Wp and 20 modules were used for our calculations. For the mounting system, the material requirements have been divided by two in order to obtain a more reliable quantitative estimate for the study being conducted.

Table 8 – Disposing masses of PV system for a household after 30 years
Source: own calculations, using data from Alsema et al. (2005) and Fthenakis et al. (2009)

Disposal of PV system for HH after 30 years in kg	
PV-modules	357.1
Inverter	24.4
Mounting system	53.8
Sum:	**435.3**

4.8 Solid Wastes from PV Manufacturing Plant Decommissioning

Presented in Table 3 are the materials expended for the plant infrastructure and their corresponding amounts that will assume the condition of waste after the 30^{th} year.

4.9 Overall Results: Inventory

As shown in the MFA diagram performed Sankey-style, first order solid material flows are accounted for together with their corresponding waste and overburden. First order materials refer here to materials that are utilized in the production of the solar cells and modules, for instance silicon, glass, and metals.

Regarding the PV modules transport and distribution step, it will be mentioned here that infrastructure waste and overburden involved in the transportation step are excluded from the analysis. Transport is merely depicted in the STAN diagram to aid to a more accurate representation of the processes transited before a manufactured good can reach the consumer.

In the system depicted below, clearly identifiable are the quantities and qualities of the flows that assume the waste condition after life expectancy is reached. The stock within the disposal process was calculated to be 1.194 kg. While the amount is arguably significant, flows such as the weight of the PV module, the virtual production waste for material supply and infrastructure decommissioning can justify it.

Overburden considered, the two material flows that bear the largest virtual overburden are those of material supply and mounting system. This can be attributed back to the large demands of metals, whose virtual overburden is fairly large as compared to the other raw materials.

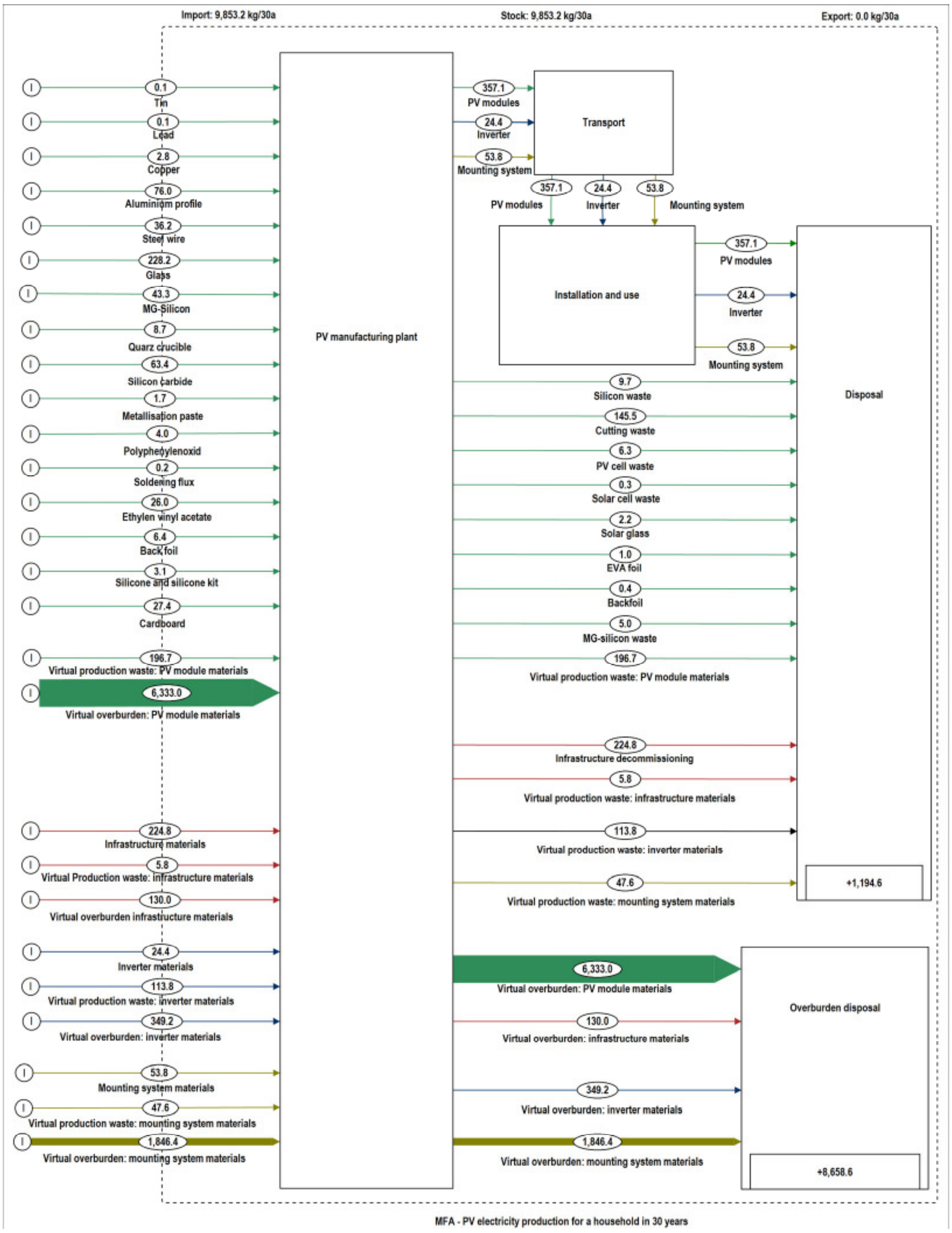

Figure 6 – MFA of PV electricity production for a household in 30 years

Source: own creation using STAN

5 System Analysis - Centralized Biomass Combustion

5.1 Overview

Spatial system boundaries for the biomass system have been defined for a biomass-fueled combustion plant in Vienna - the Vienna Simmering plant, while the temporal boundaries have been set for 30 years. The 30-year interval was chosen to represent the assumed lifetime of the plant under consideration. Although serving a combined heat and power purpose that yields a total energy efficiency of approximately 80%, the combustion plant in Simmering will be studied from the point of electricity generation only, as to achieve a feasible comparison with the photovoltaic system.

This section will cover the details of the Vienna Simmering plant and technical data on its construction, as a basis for determining and quantifying the most significant outputs and material flows for the biomass system. This will then serve as a means to achieve a valid and transparent system for biomass that can be readily used for comparison against the photovoltaic system.

The plant in Simmering officially started operation in 2006 and was built as a cogeneration plant with a high potential variation in the power-to-heat ratio. Its accessibility by road and train, and the infrastructure for feeding in electricity and heat to the Wien Energie grid were regarded as major reason to construct the Biomass plant in Vienna Simmering.

Based on state-of-the-art technology, the plant consists of the following main components: "*(1) a bunker for the woody biomass; (2) a separator for metal and oversized wood chips; (3) a dosing silo with a capacity sufficient for two hours of operation; (4) a woody biomass silo with a capacity of* $7500m^3$*, able to store the biomass needed for four days of operation; (5) a circulating fluidized bed (CFB) boiler; a selective catalytic reduction (SCR) unit for the reduction of nitrous oxides; and (7) a* *fabric filter using limestone as an additive and, if needed, activated carbon as a superior but more expensive alternative*" (Madlener and Bachhiesl, 2006).

The woody biomass needed for the plant is provided by the national forests sector that manages 15% of the 3.97 million hectares of forest in Austria. The amount of biomass needed is about 600,000m^3 fill volume (srm) that is collected within a radius of 100 km around the plant's location, and transported to a chipping yard approximately 2km away from the power plant.

Table 9 - Technical data of Vienna Simmering Biomass plant
Source: Wien Energie, 2011

Plant	**Value**	**Unit**
Average operating time	8,000	h/a
Type of operation	CFB	
Input		
Annual biomass consumption	ca. 600,000	m^3/a
	ca. 190,000	t/a
Hourly biomass consumption	ca. 75	srm/h
	ca. 24	t/h
Sand	ca. 0.3	t/h
Slaked lime	ca. 44	kg/h
Ammonia	ca. 1.1	kg/h
Output		
Bottom ash - coarse fraction	ca. 145	kg/h
Bottom ash - fine fraction	ca. 145	kg/h
Fabric filter ash	ca. 360	kg/h
Energy production		
Fuel thermal output	max. 65.7	MW_{th}
Thermal input	ca. 520	GJ/a
District heating extraction	max. 37	MW_{th}
Generator output	max. 24.5	MW_{el}
System efficiency	80	%

The circulating fluidized bed boiler with a thermal output of about 66 MW_{th} burns about 24 tons wood chips per hour and the produced steam is used in an extraction and condensation turbine to provide electricity and district heating. According to Wien Energie, in winter when the plant is working at its highest efficiency of about 80%, 12,000 homes can be heated and 48,000 can be provided with electricity, whereas in summer the efficiency of the plant sinks to about 36% because the heat produced cannot be used for district heating.

5.2 Waste Products Identification and Quantification

For centralized biomass combustion, relevant data have been gathered based on information provided by the Vienna Simmering combustion plant. Complementary data from the GEMIS database has been used to cover for unavailable information with regard to infrastructural materials.

Although the Simmering CHP plant is likely to be unique in terms of infrastructure and size, as information regarding expenditures for creation could not be obtained, assumptions were made to compensate for this lack. A similar biomass-fueled plant with the appropriate infrastructural data was taken from GEMIS and scaled up to the power capacity of Vienna Simmering. Reasons to choose this particular plant were based on similarities technology-wise: the circulating fluidized bed (CFB) combustion technology and the combined heat and power (CHP) capabilities. For the wood chipper alimenting the plant, expenditures for creation were also taken into account.

Aggregation of the useful data into four detailed steps has been performed, with each of the stages explained in the upcoming sub-chapters.

5.3 Virtual Production Waste and Virtual Overburden for Wood Chipper and Biomass Plant Infrastructure

Relevant data for both facilities in terms of expenditures for creation are shown in Table 10. It was assumed, based on information from the GEMIS database, that only steel and high density polyethylene (HDPE) were employed in significant quantities in the construction of the wood chipper. The requirements for these materials were calculated to be 449 tonnes and, 23.6 tonnes respectively.

For the biomass-fueled plant infrastructure, the two quantitatively considerable material flows are in the form of steel and cement.

Table 10 – Expenditures for creation of chipper and plant
Source: own calculations using GEMIS 4.6 database

	Demand for 1MW (t)	**Demand for PP (t)**
Chipper		
Steel	1.83E+01	4.49E+02
HDPE	9.65E-01	2.36E+01
Powerplant		
Steel	4.05E+01	9.94E+02
Cement	8.17E+02	2.00E+04
Sum:	**877.16**	**21,490.42**

Table 11 – Virtual production waste and virtual overburden of biomass power plant infrastructure
Source: own calculations using GEMIS 4.6 database

Biomass PP Infrastructure	Selected Processes in Gemis	Virtual production waste & virtual overburden			
		VPW kg/kg material	VOB kg/kg material	VPW for plant (t)	VOB (t)
Chipper	chipper-big\wood-chips-forest-DE-2010				
Steel	metal\ steel-mix-DE-2010	3.8E-01	2.4E+00	1.73E+02	1.17E+03
HDPE	chem-org\ HDPE-DE-2000	1.2E-02	3.5E-02	2.92E-01	8.19E-01
Powerplant	gasifier aCFB + cleaning\gas forestry residue (for ICE/GT)-2010 + woodgas-aCFB-forest-chips-ICE-cogen-1MW-2010/gross				
Steel	metal\ steel-mix-DE-2010	3.8E-01	2.4E+00	3.82E+02	2.59E+03
Cement	nonmetallic minerals\ cement-DE-2000	3.1E-04	2.1E+00	6.19E+00	4.17E+04
Sum:				**561**	**45,481**

5.4 Virtual Production Waste and Virtual Overburden of Auxiliary Materials

Auxiliary materials designate here the materials fed together with the wood chips to the CHP plant. Requirements for these additional materials include: limestone, sand and ammonia. The demand in tonnes was imported for 1 hour of plant operation and calculated for the 30-year lifetime (Table 12). Corresponding virtual production waste and overburden are accounted for separately in Table 13.

Table 12 – Mass of biomass and auxiliary materials for operating the plant
Source: Wien Energie, and own calculations

	Demand for 1 hour (t)	**Demand for PP (lifetime) (t)**	**Demand per HH and year (kg)**
Biomass	2.40E+01	5.76E+06	4.33E+03
Sand	3.00E-01	7.20E+04	5.41E+01
Limestone	4.40E-02	1.06E+04	7.93E+00
Ammonia	1.10E-03	2.64E+02	1.98E-01
Sum:	**24.35**	**5,842,864**	**4,389.1**

Table 13 – Virtual production waste and virtual overburden of auxiliary materials
Source: own calculations using GEMIS 4.6 database

		Virtual production waste & virtual overburden			
Auxiliary materials	**Selected processes in Gemis**	**VPW kg/kg material**	**VOB kg/kg material**	**VPW for plant in lifetime (t)**	**VOB for plant in lifetime (t)**
Sand	Xtra-quarrying\ sand-DE-2010	2.50E-05	1.09E-01	1.80E+00	7.83E+03
Limestone	Xtra-quarrying\ limestone-DE-2010	3.88E-05	2.01E-01	4.09E-01	2.12E+03
Ammonia	chem-inorg\ ammonia-DE-2010	2.51E-03	6.57E-02	6.63E-01	1.73E+01
Sum:				**2.9**	**9964.2**

Depicted in Table 14 - second and third column - are the calculated virtual production waste and virtual overburden of auxiliary materials corresponding to the annual electricity needs of one household. These amounts were multiplied by a factor of 30 to obtain the virtual production waste and virtual overburden's household share for the assumed lifetime of the plant.

Table 14 – Virtual production waste and virtual overburden of auxiliary materials per household
Source: own calculations using GEMIS 4.6 database

	Virtual production waste & virtual overburden			
Auxiliary materials	**VPW per HH and year (kg)**	**VOB per HH and year (kg)**	**VPW per HH in 30 years (kg)**	**VOB Per HH in 30 years (kg)**
Sand	1.35E-03	5.88E+00	4.05E-02	1.76E+02
Limestone	3.07E-04	1.59E+00	9.22E-03	4.78E+01
Ammonia	4.98E-04	1.30E-02	1.49E-02	3.91E-01
Sum:	**0.0022**	**7.48**	**0.065**	**224.55**

5.5 Solid Wastes during Plant Operation

The auxiliary materials expended together with the wood chips for the operation of the plant yield a certain type of solid wastes, including ash that was calculated to be 1.5% of the total content of solid waste. The waste products generated as a result of plant operation are depicted in Table 15

Table 15 – Solid wastes produced during plant operation
Source: own calculations using GEMIS 4.6 database

Waste from plant operation	**Produced per hour (t)**	**Produced in PP lifetime (t)**	**Produced per HH and year (kg)**
Bed ash and sand	2.90E-01	6.96E+04	5.23E+01
Filter ash and dry sorption product	3.70E-01	8.88E+04	6,67E+01
Sum	**0.66**	**158,400**	**119**

5.6 Solid wastes from Wood Chipper and Plant Decommissioning

Infrastructure dismantlement amounts to 21,018 tonnes in waste after its expected lifetime, as calculated based on quantities taken from GEMIS. The results can be found in Table 10.

5.7 Overall results: Inventory

The data provided in the aforementioned sub-sections on the investigated wooden biomass alternative were inventoried to produce a comprehensive and transparent representation of the MFA system which can be found in Figure 7.

Due to the Sankey-styled diagram, it can fairly be noted that the most important resource used for the system's operation is counted to be biomass, which amounts to 5,760,000 tonnes per 30 years.

For the current system under investigation, the Vienna Simmering biomass-fuelled plant, it was found that the once leaving the chipper, wood chips are transported on a 2-km distance before arriving at the plant site. In addition to the assumption that there are no wood losses due to the insignificance of the distance, the process of transport was not considered here. In consistence with the case of photovoltaics, this process was selected only to provide a better understanding of the interactions within the system.

Regarding waste generation, infrastructure decommissioning accounts for a significant 11.7% of the total amount of waste being disposed of while waste generated due to plant operation amounts to 88.3%. If the overburden disposal is considered as well, this would lead to an increase of 30 % in the stock of the disposal process.

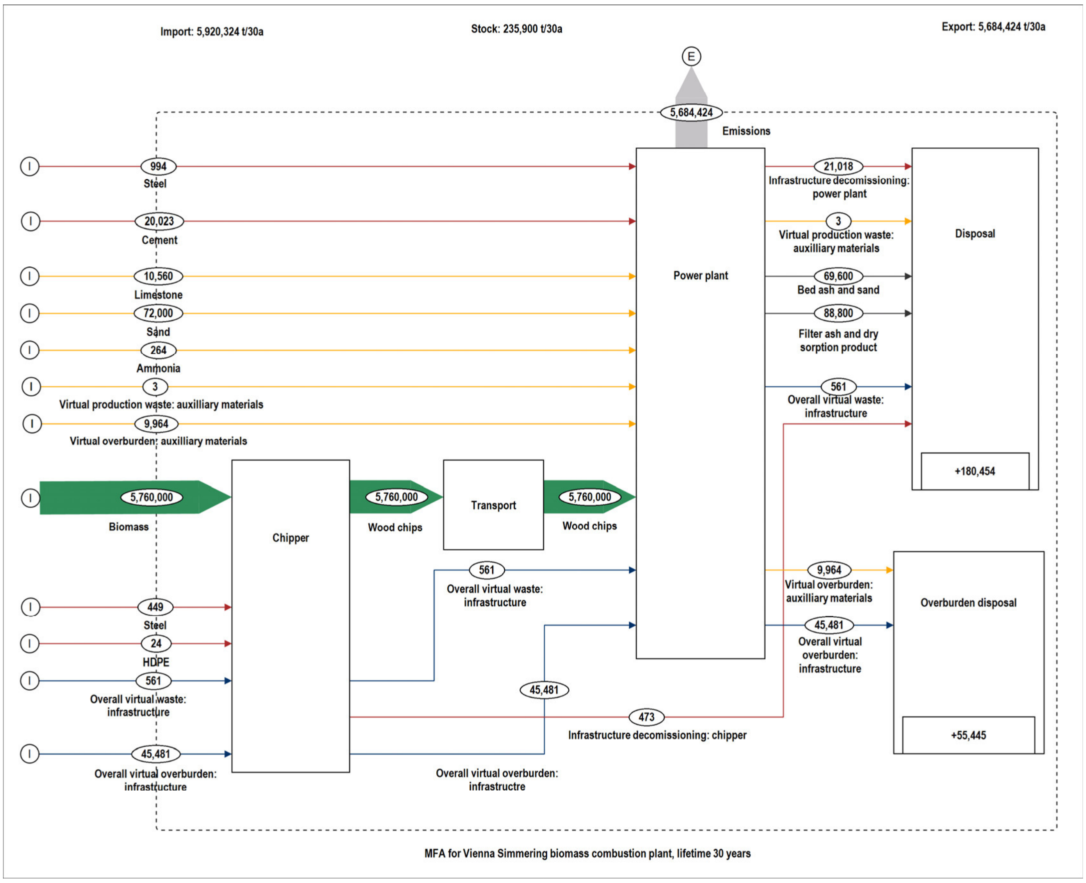

Figure 7 – MFA for Vienna Simmering biomass combustion plant, lifetime 30 years
Source: own creation using STAN

6 Final Results and Interpretation

6.1 Photovoltaic – Biomass System Comparison

While the previous two sections were aimed at capturing and detailing the solid material flows between most relevant processes within some pre-selected system boundaries, this chapter will elaborate on the key results of this study's findings in the aftermath of presenting two facilely comparable systems, analyzed using material flow analysis techniques.

To this end, the systems under scrutiny need to adhere to a set of parameters as follows: the functional unit is assumed to be 4,417 kWh, which reflects the mean annual electricity consumption of a Viennese household (Statistik Austria, 2008). The spatial system boundaries are in this case set for the average private household in Vienna, while the temporal boundary is fixed for one year.

With regard to the photovoltaic system, a detailed analysis has been performed under chapter four of this study and the data aggregated there into four steps will provide the basis for the calculations of a final system that considers the parameters described above. All other assumptions will be kept throughout this section, unless stated otherwise.

As for biomass, the final system chosen for comparison will connect to the system examined in chapter five, with the exception that its boundaries will need to be scaled down: the 24.5 MW cogeneration plant with an assumed lifetime of 30 years will be replaced by a single private household whose mean electricity demand is 4,417 kWh per year.

It should be noted here that although state-of-the-art technologies are applied to both systems under study, a loss of efficiency is connected to the biomass combustion plant when utilized solely for electricity production purposes, as assumed for this study. The cogeneration plant is designed to optimize the heat and power production as to reach an efficiency of about 80%. In turn, an estimated 37% efficiency can be expected when the plant is run only to provide Viennese households with electricity, as is the case six to seven months annually.

Before introducing the final results, it is worth mentioning that for the purpose of this paper, the calculated quantities of infrastructure materials that would result in decommissioning waste after the assumed 30-year lifetime of both the PV manufacturing facilities and the CHP plant, have been divided by the number of years as to obtain a certain amount for any given year. The graphical representation of the MFA systems in STAN has been adjusted accordingly for the virtual production waste and virtual overburden flows as well. While the three aforementioned flows depicted in the STAN figures could not stand logical scrutiny, the MFA representations are meant to be taken as annual estimations that bear scientific meaning only when kept or integrated in the appropriate context.

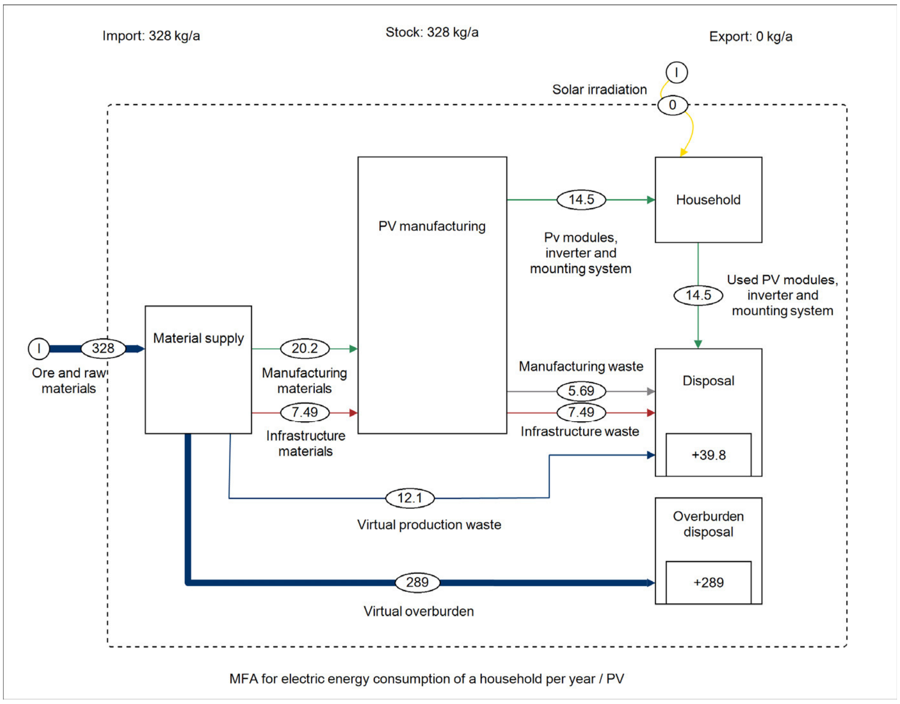

Figure 8 – MFA for electric energy consumption of a household per year / PV
Source: own creation using STAN

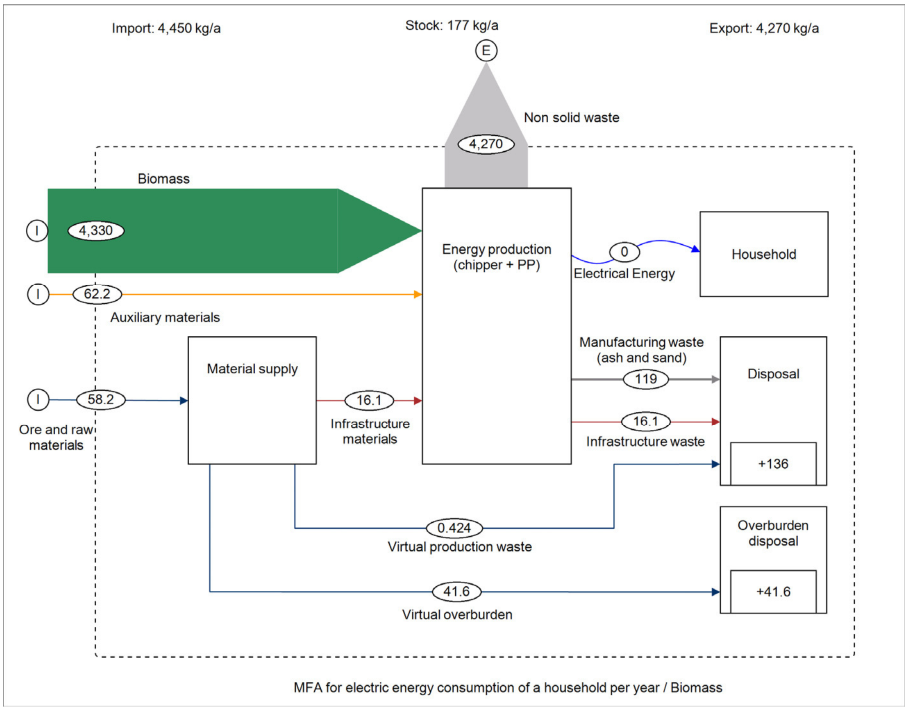

Figure 9 – MFA for electric energy consumption of a household per year / Biomass
Source: own creation using STAN

6.2 Results and Discussion

As shown in the material flow representation in figure 9, the amount of wooden biomass needed to support the electricity demand for one household in a given year equals ca. 4,330 kg, while the sum of all materials expended for the production of 4,417 kWh expands to a total of ca. 4,450 kg.

The auxiliary materials in form of sand, limestone and ammonium, employed in addition to biomass in the combustion process have been assessed (Table 14) as having a negligible virtual production waste and a virtual overburden of 7.48 kg. The manufacturing waste consisting of bed ash and sand as well as filter ash and dry sorption product are expected to result in a significant amount of 119 kg going to disposal every year.

Depicted in the STAN representation within the same “energy production” process are the chipper and the combustion plant, which cause a relatively low amount of infrastructural waste and manufacturing waste to be directed towards disposal.

In terms of findings with reference to the biomass system, it can be noticed that the third biggest material flow to the system is generated by the ore and raw materials. The virtual production waste occurs as a result of raw material extraction and processing that is assumed to take place within the process nominated as “material supply”.

A look at the sole non-solid material flow in the system would bring about a total of ca. 4,270 kg considered to be disposed of into the atmosphere as emissions.

Under the assumptions made earlier in the chapter, the assessment performed for the biomass system leads to conclusive results in terms of the solid material waste generated by the production of electricity per household in Vienna. More specifically, the amount of solid waste products disposed of in one year is bound to reach 177.6 kg, consisting of biomass combustion manufacturing waste, infrastructure decommissioning waste and a fairly large virtual production waste and virtual overburden.

Passing on to the photovoltaic system, the MFA representation indicates utterly different results with regard to not only manufacturing materials directed towards solar cell and module production, but also infrastructural materials. For both flows, the calculations show a total of 27 kg, with an additional 301 kg resulting from virtual production waste and overburden. Considering the infrastructure, construction materials amounting to 7 kg are directed towards disposal facilities each year, and the addition of 6 kg in manufacturing waste yields a sum almost equal to that of the waste arising from used PV modules, mounting system and inverter. The system under study appears to be generating a fairly large quantity of solid wastes arising to 329 kg that are stored within the "disposal" and "overburden disposal" processes.

Due to this study's time-consuming attribute, some of the processes within the systems boundaries were not as detailed as the others. Data availability also proved to be a constraint, therefore further research is desirable in both cases – for instance, in terms sub-processes connected to PV manufacturing.

The final results displayed in the previous sub-section show unanticipated key findings for each of the studied systems.

For instance when considering the PV system, it can be argued that quantitatively speaking, the amount of virtual overburden is approximately eleven fold larger than the actual materials employed. The difference can be explained by appointing to the substantial overburden that three of the materials employed in the production of the PV modules bear: the production of 1.4 kg of metallurgical-grade silicon (MG-Si) – needed for the household's requirement of PV modules - creates an overburden of 61.1 kg. The same holds true in the case of copper and aluminium profile.

Further relevant results for the photovoltaic appliances show that the amount manufacturing waste is only 2.5 times lower the actual weight of the modules, which could prove to be problematic for the PV manufacturing facilities, if recycling is not considered an option.

When analyzing the biomass combustion option virtual production waste generation could arise interest, since it hardly bears resemblance to its counterpart flow within the PV system. Reasons for this difference include the fact that the expended auxiliary materials have a fairly insignificant virtual production waste. Another explanation considers the fact that the amount of 0.42 kg reflects the share of one household to overall materials employed in the creation and operation of the power plant – considering that the biomass-fueled plant aliments the electricity needs of approximately 44.000 households.

Calculations have shown that in the case of biomass combustion, 4.45 tonnes of materials are being turned over each year in order for a household to be supplied with electricity from this renewable resource. By comparison to photovoltaics that only requires a total material turnover of 328 kg, the biomass system appears to be the less resource-efficient. Nevertheless, the biomass combustion alternative generates only 177 kg of solid waste to be disposed of on an annual basis, while the amount of waste products in the case of photovoltaics is almost twice as significant. This makes centralized biomass combustion in Vienna more sustainable in terms of waste management.

The results determined here did not include the possibility for recycling. In realistic terms though, and according to literature, technological steps are almost always taken to ensure that significant amounts of waste products, like cutting waste are recycled, are partially recycled at plant. The manufacturing waste in the case of the biomass is also almost entirely recycled to serve the construction industry's needs for raw materials.

7 Conclusions

The paramount goal of this study was to analyze by means of comparison two renewable energy options in the form of photovoltaic and biomass combustion systems, from a quantitative and qualitative approach: to this end, the solid materials produced from photovoltaic appliances and centralized biomass combustion alternatives were identified and investigated within the Vienna case study by employing material flow analysis techniques. The relevance of the MFA methodology for the present work translated into providing an overview over two highly complex systems without losing sight of the most critical processes and material flows included, as well as allowing for a determination of the major sources responsible for waste production.

The final results conducted on the one hand, to the conclusion that the photovoltaic alternative proves the less sustainable for the case of Vienna, as it generated double the amount of waste produced from biomass combustion. On the other hand, the photovoltaic appliance option was demonstrated to be the more resource-efficient one out of the two systems, in a EU member state that aims towards increased resource-efficiency goals. Based on the final results, evidence was found for the fact that centralized biomass combustion generates a thirteen fold increase in total material turnover, as compared to photovoltaics.

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Calculations for needed amount of modules for a household in Vienna	Value	Unit	Source
Yearly electrical energy consumption of a household	4417	kWh/a	Statistik Austria
Efficiency of monocrystalline silicon modules	14.0%		Environmental LCI of crystaline slicon PV module production, E.A. Alsema, M.J. de Wild-Scholten
Demand of irradiation energy for household consumption	31550	kWh/a	calculated
Mean yearly global irradiation at optimal angle in Vienna	1300	kWh/m²	European Comission, Joint Research Centre (http://re.jrc.ec.europa.eu/pvgis/imaps/index.htm)
Optimal tilt angle (facing south)	35	°	European Comission, Joint Research Centre (http://re.jrc.ec.europa.eu/pvgis/imaps/index.htm)
Module area needed for houshold consumption	**24.27**	m²	calculated
Cell area and module area of analysed PV-modules:			
Cell area of 1 module	1.12	m²	Environmental LCI of crystaline slicon PV module production, E.A. Alsema, M.J. de Wild-Scholten
Area of 1 module	1.25	m²	Environmental LCI of crystaline slicon PV module production, E.A. Alsema, M.J. de Wild-Scholten
Modules needed for a household in Vienna installed at an optimal angle:	19.42	pcs	calculated
Modules needed rounded off to:	**20**	**modules**	calculated

Life cycle inventory data for production of monocrystalline silicon modules

Product	solid Materials needed	solid wastes	amount		per cell	for 1 module	for 20 modules	solid materials in kg	waste in kg	yearly amounts
							20			(divided by 30years)
Polycryst. silicon			**1**	kg						
	MG-silicon		1.13	kg	0.0279	2.1670	43.3403	43.3403		1.4447
		mg-silicon waste	0.13	kg	0.0032	0.2493	4.9861		4.9861	0.1662
mono-Si wafer			**1**	**m²**	0.0156	1.2137	24.2748			
	poly-Si		**1.58**	kg	0.0246	1.9177				
	quartz crucible		0.36	kg	0.0056	0.4369	8.7389	8.7389		0.2913
	glass		0.01	kg	0.0002	0.0121	0.2427	0.2427		0.0081
	steel wire		1.49	kg	0.0232	1.8085	36.1695	36.1695		1.2057
	silicon carbide (SiC)		2.61	kg	0.0407	3.1679	63.3574	63.3574		2.1119
		silicon waste	0.4	kg	0.0062	0.4855	9.7099		9.7099	0.3237
		cutting waste	6	kg	0.0936	7.2825	145.6491		145.6491	4.8550
mono-Si cell (156cm²)			**1**	**pc**		72.0000	1440.0000			
	mono-Si wafer (156cm²)		**1.06**	**pc**		77.8040	1556.0800			
	phosphorus paste		0.0000227	kg		0.0017	0.0333	0.0333		0.0011
	metallisation paste		0.00117	kg		0.0859	1.7176	1.7176		0.0573
	polystyrene, expandable		0.00000636	kg		0.0005	0.0093	0.0093		0.0003
		photovoltaic cell waste	0.00431	kg		0.3164	6.3271		6.3271	0.2109
Module, c-Si			1	**pc**						
	mono-Si cell		**73.4**	**pc**						
	Aluminium profile		3.8	kg		3.8000	76.00	76.00		2.5333
	Polyphenylenoxid		0.2	kg		0.2000	4.00	4.00		0.1333
	Glass sheet		11.4	kg		11.4000	228.00	228.00		7.6000
	Ethylen Vinyl Acetate		1.3	kg		1.3000	26.00	26.00		0.8667
	Back foil		0.32	kg		0.3200	6.40	6.40		0.2133
	Copper		0.14	kg		0.1400	2.80	2.80		0.0933
	Tin		0.007	kg		0.0070	0.14	0.14		0.0047
	Lead		0.004	kg		0.0040	0.08	0.08		0.0027
	Nickel		0.0002	kg		0.0002	0.00	0.00		0.0001
	Soldering flux		0.01	kg		0.0100	0.20	0.20		0.0067
	Silicone		0.0029	kg		0.0029	0.06	0.06		0.0019
	Silicone kit		0.15	kg		0.1500	3.00	3.00		0.1000
	Cardboard		1.37	kg		1.3700	27.40	27.40		0.9133
		solar cell waste	0.015	kg		0.0150	0.30		0.30	0.0100
		solar glass	0.11	kg		0.1100	2.20		2.20	0.0733
		Ethylvinylacetate foil	0.05	kg		0.0500	1.00		1.00	0.0333
		Back foil	0.02	kg		0.0200	0.40		0.40	0.0133
							Sum:	**527.6911**	**170.5722**	**kg**
							mass of materials used minus waste produced:			
									357.1189	**kg**

Prod. waste & overburden of materials used for manufacturing PV modules (data from GEMIS)						For a household in kg per year			For a household in kg per 30 years		
Material	**Name in GEMIS database**	**Production waste**		**Overburden**		**kg needed**	**Prod waste**	**Overburden**	**kg needed**	**Prod waste**	**Overburden**
MG-silicon	Fabrication\silicon-MG-DE-2010	0.0691	kg	42.3019	kg	1.4447	0.0998	61.1126	43.34	2.99	1833.38
Quartz crucible	Xtra-quarrying\quarz sand-DE-2000	0.0001	kg	0.1520	kg	0.2913	0.0000	0.0443	8.74	0.00	1.33
Glass & glass sheet	nonmetallic minerals\glass-flat-DE-2000	0.0140	kg	0.6734	kg	7.6081	0.1063	5.1231	228.24	3.19	153.69
Steel wire	metal\steel-mix-DE-2010	0.3847	kg	2.4209	kg	1.2057	0.4639	2.9187	36.17	13.92	87.56
Silicon carbide (SiC)	chem-inorg\silicon carbide	0.0682	kg	1.1685	kg	2.1119	0.1440	2.4678	63.36	4.32	74.03
Phosphorus paste	chem-inorg\phosphorus paste	51.6000	kg	1.8060	kg	0.0011	0.0573	0.0020	0.03	1.72	0.06
Metallisation paste	chem-inorg\metallisation paste	0.0000	kg	1.0042	kg	0.0573	0.0000	0.0575	1.72	0.00	1.72
Polystyrene, expandable	chem-org\PS-DE-2010	0.0043	kg	1.5885	kg	0.0003	0.0000	0.0005	0.01	0.00	0.01
Aluminium profile	metal\aluminium-DE-2010	1.1542	kg	51.4567	kg	2.5333	2.9241	130.3569	76.00	87.72	3910.71
Polyphenylenoxid	chem-org\polyphenylenoxide	0.0209	kg	6.2015	kg	0.1333	0.0028	0.8269	4.00	0.08	24.81
Ethylen Vinyl Acetate	chem-org\EVA	0.0148	kg	0.2657	kg	0.8667	0.0129	0.2303	26.00	0.39	6.91
Back foil	chem-org\back foil for PV-modules-DE-2005	0.0127	kg	1.6807	kg	0.2133	0.0027	0.3585	6.40	0.08	10.76
Copper	meta\copper-DE-mix-2010	29.0144	kg	58.9659	kg	0.0933	2.7080	5.5035	2.80	81.24	165.10
Lead	metal\lead-DE-mix-2010	0.0031	kg	2.7627	kg	0.0027	0.0000	0.0074	0.08	0.00	0.22
Nickel	metal\nickel-DE--2010	57.2600	kg	113.4627	kg	0.0001	0.0076	0.0151	0.00	0.23	0.45
Cardboard	pupl-paper\kraft liner-EU	0.0301	kg	2.2710	kg	0.9133	0.0275	2.0742	27.40	0.82	62.23
Tin	n/a	n/a		n/a		0.0047	n/a	n/a	0.14	n/a	n/a
Soldering flux	n/a	n/a		n/a		0.0067	n/a	n/a	0.20	n/a	n/a
Silicone kit	n/a	n/a		n/a		0.1000	n/a	n/a	3.00	n/a	n/a
Silicone	n/a	n/a		n/a		0.0019	n/a	n/a	0.06	n/a	n/a
Sum:						**17.59**	**6.56**	**211.10**	**527.69**	**196.71**	**6332.97**

Calculating masses of inverter and mounting system											
Inverter:											
Peak powor		2500	Wp	3300	Wp	Production waste	Overburden	**Production waste & overburden of 3300W inverter for a household in kg**			
Materials needed	**Name in GEMIS database**					**(kg/kg)**	**(kg/kg)**	**PW for 30 years**	**OB for 30 years**	**PW per year**	**OB per year**
Steel	metal\steel-mix-DE-2010	9.8	kg	12.94	kg	0.3847	2.4209	4.9769	31.3165	0.1659	1.0439
Aluminium	metal\aluminium-DE-2010	1.4	kg	1.848	kg	1.1542	51.4567	2.1331	95.0919	0.0711	3.1697
Printed circuit board	**n/a**	1.8	kg	2.376	kg	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
Copper (half weight of transformer)	meta\copper-DE-mix-2010	2.75	kg	3.63	kg	29.0144	58.9659	105.3221	214.0462	3.5107	7.1349
Steel (half weight of transformer)	metal\steel-mix-DE-2010	2.75	kg	3.63	kg	0.3847	2.4209	1.3966	8.7878	0.0466	0.2929
Sum		18.5	kg	**24.42**	kg			**113.8286**	**349.2424**	**3.7943**	**11.6414**
Mounting system: (slanted roof)	Lifetime assumed is 60 years (source Fthenakis) so the mass is divided by 2, to calculate need for household in 30 years										
Materials needed	**Name in GEMIS database**					Production waste	Overburden	**PW for 30 years**	**OB for 30 years**	**PW per year**	**OB per year**
Data for 1m² from EcoInvent		kg/m²		HH in 30 years		(kg/kg)	(kg/kg)	kg	kg	kg	kg
Aluminium	metal\aluminium-DE-2010	2.8		35	kg	1.1542	51.4567	40.3987	1800.9834	1.3466	60.0328
Steel	metal\steel-mix-DE-2010	1.5		18.75	kg	0.38473	2.4208793	7.2137	45.3915	0.2405	1.5130
Sum				**53.75**				**47.6124**	**1846.3749**	**1.5871**	**61.5458**
Sum inverter and mounting system:				**78.17**	**kg**			**161.4410**	**2195.6173**	**5.3814**	**73.1872**

Creation of solar cell production factory		(Source: EcoInvent 2009)										
Lifetime		25	a									
Annual prod		100000	m^2									
Production in lifetime		2500000	m^2									
Multiplying with (30/25) to calculate data for 30 years		1.2										
Overall prod. in 30 years		3000000	m^2			**Ratio of Household share to overall production in 30 years =**				**8.09162E-06**		
						Demand of materials		**Production waste and Overburden**		**PW & OB of factory per household in 30 years**		
Expenditures for creation:	**Name in GEMIS database**			**For 30 years**		**per Household in 30 years**		PW (kg/kg)	OB (kg/kg)	PW	OB	
Steel reinforced	metal\steel-mix-DE-2010	190000	kg	228000	kg	1.8449	kg	0.38473	2.4208793	0.7098	4.4663	kg
Steel low-alloy	metal\steel-mix-DE-2010	110000	kg	132000	kg	1.0681	kg	0.38473	2.4208793	0.4109	2.5857	kg
Brick	nonmetallic minerals\clay bricks	506	kg	607.2	kg	0.0049	kg	0.00014129	0.30849	0.0000	0.0015	kg
Concrete	nonmetallic minerals\concrete-DE-2010	4320000	kg	5184000	kg	41.9469	kg	0.00019768	0.44618	0.0083	18.7159	kg
Metal working machine	metal\steel-mix-DE-2010	10000	kg	12000	kg	0.0971	kg	0.38473	2.4208793	0.0374	0.2351	kg
Sum:		4630506	kg	**5556607.2**	kg	**44.9619**	**kg**			**1.1664**	**26.0044**	**kg**

Calculations for household consumption			
Houshold consumption per year		4417	kWh
Calculation TJ to kWh	1TJ =	277777.78	kWh
Calculation kWh to TJ	1kWh =	0.0000036	TJ
Calculation MWh to TJ	1MWh =	0.0036	TJ
Houshold consumption per year		0.0159012	TJ
Mean household power consumption		0.5038786	kW
Household consumption in 30 years		0.477036	TJ

Powerplant data (Simmering plant, max. electricity production)				Per hour	Per year	In 30 years	Per household, per year
Power	24.5	MW	**Auxiliary materials used at plant:**	kg/h	kg/a	kg	kg
Operating time per year	8000	h	Sand	300	2.40E+06	7.20E+07	5.41E+01
Lifetime	30	a	Limestone	44	3.52E+05	1.06E+07	7.93E+00
Overall production (MWh)	5880000	MWh	Ammonia	1.1	8.80E+03	2.64E+05	1.98E-01
Overall production (in TJ)	21168	TJ	**Solid wastes produced by plant:**				
Supporting households through 30 years	44374		Bed ash and sand	290	2.32E+06	6.96E+07	5.23E+01
Biomass needed	24	t/h	Filter ash and dry sorption product	370	2.96E+06	8.88E+07	6.67E+01
Biomass needed for lifetime of plant	5.76E+09	kg	Ash amount (=solid wastes - sand)	360	2.88E+06	8.64E+07	6.49E+01

GEMIS process: woodgas-aCFB-forest-chips-ICE-cogen-1MW-2010/gross		Expanditures for creation			
Process chain		steel	HDPE	cement	
Biomass-residues					
Xtra-residue\wood-DE-forest-2010					
chipper-big\wood-chips-forest-DE-2010	→	18335	965	0	kg/MW
gasifier aCFB + cleaning\gas forestry residue (for ICE/GT) -2010	→	20576.1	0	617284	kg/MW
woodgas-aCFB-forest-chips-ICE-cogen-1MW-2010/gross	→	20000	0	200000	kg/MW
	sum:	58911.1	965	817284	kg/MW
Expenditures for creation 24,5MW (chipper only)		**449207.5**	**23642.5**	**0**	**kg**
Expenditures for creation 24,5MW (gasifier and plant only)		**994114.45**	**0**	**2.00E+07**	**kg**
Expenditures for creation for 24,5MW plant		**1443321.95**	**23642.5**	**20023458**	**kg**

Demand for Infrastructure materials and biomass per household								
	Biomass		**Steel**	**HDPE**	**Cement**		**Infrastructure materials sum**	
For a year	**4326.86**	**kg**	1.08	0.02	15.04	kg/a	16.14	kg/a
For 30 years	**129805.71**	**kg**	32.53	0.53	451.24	kg/30a	484.30	kg/30a

Auxiliary materials		Production waste & overburden				Plant lifetime (30 years)		Per Household in 30 years		Per houshold, per year	
	GEMIS process names	PW		OB		PW (kg)	OB (kg)	PW (kg)	OB (kg)	PW (kg)	OB (kg)
Sand	Xtra-quarrying\sand-DE-2010	2.50E-05	kg/kg	1.09E-01	kg/kg	1.80E+03	7.83E+06	4.05E-02	1.76E+02	1.35E-03	5.88E+00
Limestone	Xtra-quarrying\limestone-DE-2010	3.88E-05	kg/kg	2.01E-01	kg/kg	4.09E+02	2.12E+06	9.22E-03	4.78E+01	3.07E-04	1.59E+00
Ammonia	chem-inorg\ammonia-DE-2010	2.51E-03	kg/kg	6.57E-02	kg/kg	6.63E+02	1.73E+04	1.49E-02	3.91E-01	4.98E-04	1.30E-02
Sum						**2.87E+03**	**9.96E+06**	**6.47E-02**	**2.25E+02**	**2.16E-03**	**7.48E+00**

Infrastructure materials		Production waste & overburden				Plant lifetime (30 years)		Per Household in 30 years		Per houshold, per year	
	GEMIS process names	PW		OB		PW (kg)	OB (kg)	PW (kg)	OB (kg)	PW (kg)	OB (kg)
Steel	metal\steel-mix-DE-2010	3.8E-01	kg/kg	2.6E+00	kg/kg	5.54E+05	3.77E+06	1.25E+01	8.49E+01	4.17E-01	2.83E+00
HDPE	chem-org\HPDE-DE-2000	1.2E-02	kg/kg	3.5E-02	kg/kg	2.92E+02	8.19E+02	6.57E-03	1.85E-02	2.19E-04	6.15E-04
Cement	nonmetallic minerals\cement-DE-2000	3.1E-04	kg/kg	2.1E+00	kg/kg	6.19E+03	4.17E+07	1.39E-01	9.40E+02	4.65E-03	3.13E+01
Sum						**5.61E+05**	**4.55E+07**	**1.26E+01**	**1.02E+03**	**4.21E-01**	**3.42E+01**

Overall production waste and overburden per household					
		PW		OB	
	Per year	0.423553883	kg/a	41.64996647	kg/a
	In 30 years	12.7066165	kg/30a	1249.498994	kg/30a

Sum of overall production waste and overburden and Infrastructure materials per household			
	Per year	58.21692102	kg/a
	In 30 years	1746.507631	kg/30a