Bachelor thesis

LIFE CYCLE ASSESSMENT OF A CONVENTIONAL FLOAT GLASS PRODUCTION AND COMPARISON WITH REGENERATIVE ALTERNATIVES

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Abstract

From a global perspective to a detailed process, this thesis exposes the actual environmental situation and the main factors that condition it. After a quick review of reasons why the situation should change, the study exposes the human activities that cause the greater impacts. This target leads the work to focus on the glass industry because it is part of the energy-intensive manufacture industrial sector.

First of all, the life cycle assessment (LCA) is introduced as a tool to analyse the environmental impacts of a product or service. In this thesis, an LCA is carried out to evaluate the production of one tonne float glass.

Secondly, the goal and the scope of the LCA are defined. The life cycle of flat glass is contemplated from cradle to gate, which includes the raw material acquisition and the energy and material production. The manufacture phase, which includes the energy and material production, is driven in a comparative manner for different systems:

A conventional production system which is mainly powered by natural gas

A regenerative production system which is only powered by electricity

A regenerative production system which is powered by renewable gas from Power-to-Gas

The approach on this LCA is derived from the international standards ISO 14040 and ISO 14044 and its analysis is assisted by the software "Umberto" with the databases "ecoinvent" version 3.3.

Thirdly, the product system with its production variations is accurately described in the inventory analysis, where the inputs and outputs of each process are stated and related to the functional unit. This inventory is gathered on the cumulative energy demand and the cumulative raw material demand.

Afterwards, the impact categories global warming potential, terrestrial acidification and water, fossil and ozone depletion are assessed and compared between the conventional and the regenerative production systems.

At the end, a critical reflection and outlook about the complete process is made.

Contents

Acronyms and abbreviations

Al_2O_3	Aluminium oxide
bq = s^{-1}	Becquerel
CaO	Calcium oxide
CED	Cumulative energy demand
CEN	European Committee for Standardization
CFP	Carbon Footprint of a Product
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CRD	Cumulative raw material demand
EMS	Environmental Management System
FD	Fossil depletion
GJ	gigajoule
GWP	Global warming potential
H_2	Hydrogen
H_2O	Water
J	Joule
K_2O	Potassium oxide
kg	kilogram
kWh	kilowatt hour
LCA	Life cycle assessment
LCI	Life cycle interpretation
LCIA	Life cycle inventory assessment
m^3	cubic meter
MgO	Magnesium oxide
MJ	megajoule

Na_2O	Sodium oxide
NG	Natural gas
NH_3	Ammonia
NO_x	Nitrogen oxides
O_2	Oxygen
OD	Oxone depletion
PEM	Polymer Electrolyte Membrane
PtG	Power-to-Gas
r-gas	renewable gas
SiO_2	Silicon dioxide
SO_3	Sulphur trioxide
T	tonne
TA	terrestrial acidification
TWh	terawatt hour
UNFCCC	United Nations Framework Convention on Climate Change
W	Watt
WD	Water depletion

0 Introduction

Future on Earth is one of the main worries and incentives for investigation. A proof of it is the United Nations Framework Convention on Climate Change (UNFCCC). Adopted during the Rio de Janeiro Earth Summit in 1992 and ratified by 196 states, the so-called State Parties, it organises an annual Conference abbreviated as COP. The most important and recent commitment was the Paris Agreement in COP 21 on November 2015 with the 196 states aimed at limiting global warming to less than two degrees Celsius. Moreover, it was the most attended conference with the largest number of global stakeholders, decision makers from across the globe representing 43 countries and over 80 world class speakers including country Ministers, industry CEOs and international thought-leaders [1].

Even if the Paris Agreement has no compulsory requirements, it states the preoccupation and confirms the believe that Thomas Stocker, Co-Chair of Working Group I for the Intergovernmental Panel on Climate Change (IPCC) explains in three key messages [2]:

- A warming in the climate system is unequivocal. That is based on the observations at the multiple lines of independent evidences.
- Human influence on the climate system is clear. This is resulting from the combination of model simulations with the observed climate change.
- Continued greenhouse gas emissions cause further climate change and constitute a multi-century commitment in the future.

The conclusion from the implicated states and T. Stocker is shared: "Limiting climate change requires substantial and sustain reductions in greenhouse gas emissions". [2]

Every state of the European Union, being part of the Paris Agreement as many other states, have summited their Intended Nationally Determined Contributions (INDCs) towards achieving the objective of the Convention [3] [4]. For example, Germany aims to cut greenhouse gas emissions (GHG) by 40 percent by 2020 and up to 95 percent in 2050, compared to 1990 levels. The share of renewables in gross final energy consumption is to rise to 60 percent by 2050. Renewables are to make up a minimum of 80 percent of the country's gross power consumption by the middle of the century [5].

These goals have been set considering the evolution of population and industry and its end-energy demand [6]. The solution that Germany propose is based on three principles:

- Efficiency: reaching more energy and resource efficiency across all areas.
- Renewable energy: expanding renewable energy and its use to all demand areas, particularly to power generation.
- Integrated energy: direct or indirect use of renewable electricity across all application areas for the complete substitution of fossil fuels and raw materials.

In order to succeed, Germany is founding some investigation projects. One of them, which is included in this thesis, is Power-To-X (PtX). Focusing on integrated energy in the industry, it does not seek to substitute each non-renewable energy for a renewable one. PtX techniques should be integrated in the processes according with their potential. Power-to-Heat (PtH) chases to use regenerative energy for heating just like Power-to-Gas (PtG) and Power-to-Liquid (PtL) pursues to substitute fossil fuels and raw material with regenerative alternatives.

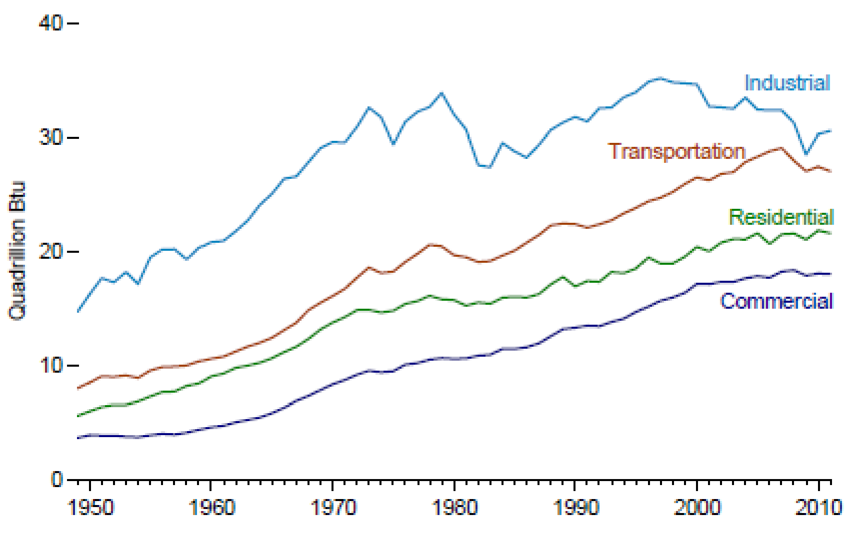
As the main objective of using regenerative energy is to emit less GHG, there should be an independent study to analyse whether the proposed solution is less polluting than the substituted process or not. This thesis seeks with a Life Cycle Assessment to focus precisely to the environmental impacts (such as GHG emissions) of the regenerative and non-regenerative processes to compare and localize the weaknesses and strengths of each one.

0.1 Reasons to carry out the study

Due to the physical proves of climate change and its current and future prospected impacts to humanity and life on Earth, scientifics and researchers pursue solutions or mitigation strategies to cope with the negative effects.

The Intergovernmental Panel on Climate Change explains in the technical Summary of the Contribution of Working Group I that the dominant factor in altering the balance of incoming and outgoing energy in the Earth-atmosphere system is the increasing concentration of various greenhouse gases in the atmosphere. “Several of the major greenhouse gases occur naturally but increase in their atmospheric concentrations over the last 250 years are due largely to human activities. Other greenhouse gases are entirely the result of human activities.” [7]

Proven this, the focus gets to the human activities, which emit greenhouse gases. The International Energy Outlook 2016 emitted by the EIA differentiates four end-use sectors: industrial, transportation, residential and commercial. The sector that consumes most energy whether it is electricity, natural gas, coal, liquid fuels or renewable fuels is the industrial sector. The industrial sector consumes about 54% of the world’s total delivered energy (measured as the heat content of energy at the site of use. [8]



Graphic 1 Total consumption by end-use sectors
Source: [8]

The graphic shows the evolution of total consumption by end-use sector from 1949 to 2011 in quadrillion British thermal unit (10^{15} Btu). It manifests that the industrial sector consumes more energy than the others.

Even if the industrial sector is the greatest consumer of energy, at the moment, a larger research is geared to other sectors like transportation, where electric vehicles are being introduced to reduce the greenhouse gas emissions. That is the main reason to carry out this study about an industrial process.

As a result, this study is done in cooperation with the project "System analysis and integration of Power-to-X in the context of renewable electricity as primary energy", SPIKE [9]. Boosted by the Bundesministerium für Bildung und Forschung in Germany, the project examines the technologies used by energy-intensive industries and seeks the integration of regenerative alternatives (Power-to-X). This study intends to compare both technologies for a specific industry sector to demonstrate the difference participation in the global warming.

1 The life cycle assessment

A Life Cycle Assessment (LCA) is a standardized evaluation of the environmental impacts of a product or service during all the stages of its life, “from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal” [10]. This complete circle is referred as cradle-to-grave. Nevertheless, an LCA can also analyse exclusively a part of this circle exposing always its boundaries.

The European Committee for Standardization CEN approved on 19 June 2006 the texts EN-ISO-14040:2006 [10] and EN ISO 14044:2006 [11] where the LCA is described. These standards serve to standardize the methodology of LCAs and are the ones followed in this study.

Two of the principles of an LCA are transparency and comprehensiveness. Due to the amount of data used in the study and the specific characteristics, it is asked to show and explain calculations, assumptions, data collection, boundaries, cut-off criteria and allocations “in order to ensure a proper interpretation of the results” [10]. Considering all attributes and aspects within one study allows a comprehensive evaluation and a comparison from a global perspective.

There are four phases in an LCA study:

1st. The goal and scope definition phase

The goal defines the application, audience and reasons for carrying out the study while the scope includes the product system, the system boundary and the level of detail. The scope may vary during the iterations in order to meet the goal.

2nd The Inventory analysis phase (LCI)

This phase involves data collection and calculation to quantify relevant inputs and outputs of a product system.

3rd The Impact Assessment phase (LCIA)

The procedure of the LCIA is to select impact categories (classes representing environmental issues of concern), category indicators (quantifiable representations) and characterization models, to classify the LCI results in these categories and to calculate the result of each category.

4th The interpretation phase

The life cycle interpretation puts together the results of the LCI and LCIA to verify if they are consistent with the defined goal and scope. In this last phase the explanation of conclusions, limitations and recommendations is given.

A representative characteristic from LCAs is the functional unit which provides a reference to which the inputs and outputs are related. Another characteristic is that it is a relative approach. “LCA is a relative approach, which is structured around a functional unit. This functional unit defines what is being studied. All subsequent analyses are then relative to that functional unit, as all inputs and outputs in the LCI and consequently the LCIA profile are related to the functional unit.” [10]

"LCA is one of several environmental management techniques (e.g. risk assessment, environmental performance evaluation, environmental auditing, and environmental impact assessment) and might not be the most appropriate technique to use in all situations. LCA typically does not address the economic or social aspects of a product…" [10]. Because of this, there is a short comparison of methods and the reasoning for the election in the next section.

1.1 Overview of other methods for identifying environmental impact

- Carbon Footprint of a Product CFP

Consulting the International Standard published by the Deutsches Institut für Normung DIN EN ISO 14067 [12], the Carbon Footprint of a Product can be consistent with and part of a Life Cycle Assessment. Although both methods have the same structure and principles, the Carbon Footprint of a Product only addresses the impact category "climate change" while the Life Cycle Assessment have this one and many others.

- Environmental Impact Assessment EIA

The Environmental Impact Assessment is a procedure rigorously described in the European Union Directive and has by law to be used for large scale developments (e.g. highway).

An EIA has to contain a description of the project and the alternatives that have been considered, an evaluation of the environment, which may be affected (e.g. landscape, fauna) and the significant effects, the possible mitigation, a non-technical summary addressed to the public and an explanation of technical difficulties. [13]

The purpose of this assessment is to accept or reject the project.

The Environmental Impact Assessment corresponds to the Life Cycle Impact Assessment phase of an LCA. Nevertheless, different methodologies are applied. The compulsoriness of the EIA leads the assessment while the LCIA can select the impacts considering the goal and iterate.

- Environmental Management System EMS

An Environmental Management System is a structured part of a working group that establishes policies, objectives and processes taking into account the environmental impact of the activity or product. The purpose of this EMS is to prevent or mitigate environmental impacts, fulfil the environmental obligations, improve environmental performance by influencing the way the organization's products and services are designed, manufactured, distributed, consumed and disposed. [14]

The Environmental Management System uses a life cycle perspective to prevent environmental impacts from being unintentionally shifted elsewhere. An organization requires a previous knowledge of the environmental impacts of a product (which could be provided by an LCA) in order to know how to apply an Environmental Management System afterwards. Due to this, an LCA and an EMS can be complimentary.

1.2 Reasons for choosing the LCA

The method elected to develop this thesis is the Life Cycle Assessment because it sets a framework in which comparisons can be waged; this characteristic is significant since this study intends to compare different processes.

Furthermore, the software UMBERTO NXT LCA version 7.1 developed by ifu Hamburg GmbH [15] will assist the LCA. Creating a model, introducing several inputs and working together with the database “ecoinvent” version 3.3 [16] the impact categories can be calculated in an iterative way.

2 Goal

The aim of this project is to analyse the environmental impact of the production of flat glass in the glass industry in Germany. A Life Cycle Assessment is carried out in a comparative manner between:

- A conventional product system, which is based on the technologies used nowadays and its main source of energy is natural gas.
- An electrically-powered product system, which sources of energy are only renewable. This regenerative alternative needs different installations than the conventional product system.
- A regenerative product system based on the nowadays technologies, which changes the main source of energy to renewable gas (r-gas) generated with a Power-to-Gas (PtG) technology system.

The three cases' comparison will be driven for a tonne of float glass with standardize properties and composition.

The potential environmental impacts are checked by the indicators: global warming potential (GWP), cumulative energy demand (CED), cumulative raw materials demand (CRD), water, fossil and ozone depletion and terrestrial acidification.

3 Scope

The float glass industry, as part of the glass industry, is part of the energy-intensive manufacture industrial sector. The other industrial sectors are the nonenergy-intensive manufacturing sector and nonmanufacturing sector [8]. This classification proves the great energetic, and consequently environmental, impact of the glass industry.

The model created in "Umberto" [15] is calculated from cradle to gate. This means that the system within the boundaries comprises the extraction of raw materials, the basic material production and the product manufacturing as it is shown in the Figure 1.

Even though the model created is calculated from cradle to gate, the extraction of raw materials does not change for the different product systems. Therefore, the comparative analysis is from gate to gate, which refers only to the product manufacturing.

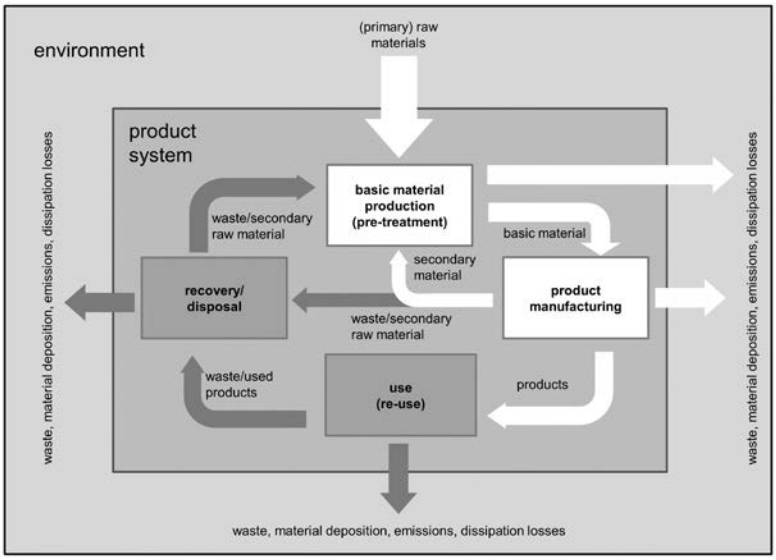


Figure 1 Cradle-to-gate view of the product
Source: [17]

For the three product systems analysed, the packaging process and transportation of the product to the selling point are not comprised because there is no literature regarding these aspects. It is comprised, though, the glass cut off the ribbon. This internal cullet is taken from the cutting process of the product manufacturing to the basic material production as secondary material.

All the renewable energies regarded in this study has no GHG emissions, nor use they any non-renewable source.

3.1 Product systems to be studied

The glass industry and more particularly the production of flat glass in Europe is the addressed target group for this LCA. The product systems studied are the conventional production of float glass by a cross-fired regenerative furnace powered by natural gas, an electrically-heated furnace and a cross-fired regenerative furnace powered by PtG.

A general overview of the product system is shown in Figure 2. At the beginning, the solid raw materials and cullet (recycled glass) are poured together forming the batch and driven to the melting tank (n.2 in the Figure 2). At this point the batch is molten at around 1300-1550ºC. The batch stays 60 to 72 hours in the melting tank moving forward with a decreasing temperature that reaches 1100ºC at the exit. This melting process can be divided into the primary melting, where most of the chemical and physical reactions occur, giving off water, carbon dioxide, oxides of nitrogen and oxides of sulphur; and the fining, where the melt is naturally or induced homogenized by removing the bubbles from the melt. [18]

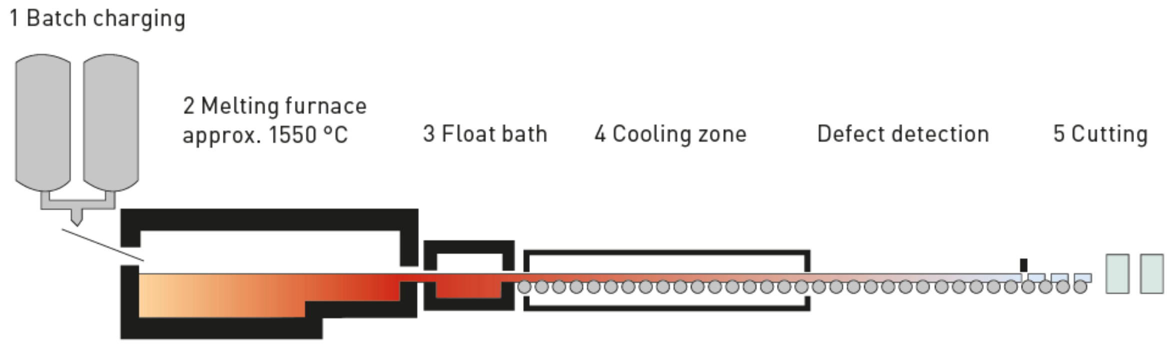


Figure 2 Production of float glass
Source: [19]

Through a sprout the batch is spilled over a molten tin bath (n. 3 in the Figure 2) where gravity and the tin surface lead the molten glass to form a uniform thickness and almost perfect flatness. There are two ways to flatter glass. The most used (for 96,5% of the flat glass), and analysed in this study, is flattered in a tin bath, characteristic which brings the flat glass to be also known as float glass. [18]

At the exit of the float bath, at 600ºC, the glass ribbon is taken out by lift-out rollers and is passed through a temperature-controlled tunnel, the lehr (n. 4 in the Figure 2), to be annealed. At the beginning of the lehr, sulphur dioxide is sprayed to protect the glass against the contact of the rollers. In this annealing process, glass is gradually cooled from 600ºC to 60ºC in order to reduce residual stresses. Once it is cold, the edges of the ribbon that bear roller marks are cut off (n. 5 in the Figure 2) and recycled to the furnace as cullet. The ribbon is cut in the last step according to demand and packed, secured to be stored or loaded on means of transport. [18]

On-line coatings can be applied to improve the performance of the glass, even though these are only in a few industries implemented. The coatings are predominantly made after leaving the plant by each customer. [18]

3.1.1 Cross-fired regenerative furnace powered by natural gas

The burner ports are situated along the furnace side walls, normally covering almost the complete length. Each port is provided with 2 – 4 burners, according to the furnace size [20]. The waste heat in the waste gases is used to preheat air prior to combustion. This is achieved by passing the waste gases through a chamber containing refractory material, which absorbs the heat. This two regenerator chambers are located on the sides of the furnace [18].

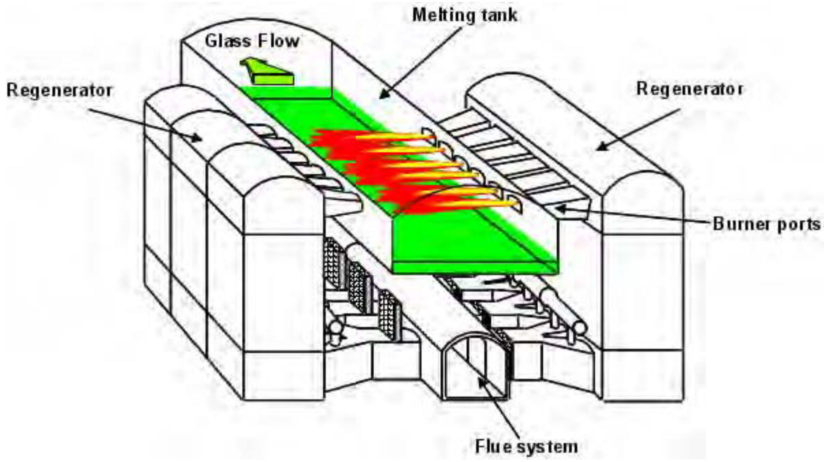


Figure 3 Cross-fired regenerative furnace
Source: [18]

The furnace fires on only one of two sets of burners at any one time. The flame travels from one side of the furnace to the other and the waste gases are exhausted exactly opposite the entry burner port. After a predetermined period, usually 20 minutes, the firing cycle of the furnace is reversed, and the combustion air is passed through the chamber previously heated by the waste gases. [18]

Float glass is produced almost exclusively with cross-fired regenerative furnaces. In the glass industry cross-fired regenerative furnaces are the most employed furnaces for large capacity installations (>500 tonnes/day). [18]

3.1.2 Electrically-heated furnace

Electricity can provide resistive heating when passing a current through the molten glass by Joule's first law. The electrically-heated furnace is made of a refractory lined box, often square or round, supported by a steel frame with electrodes inserted either from the side, from the top or from the bottom of the furnace. The batch material is charged from the top and it gradually melts from the bottom upwards, which gives these furnaces the name "cold-top". The cold batch in the surface acts, at the same time, as a good heat insulator [18,20]

For the electric furnaces a bag filter is enough to collect the dust generated by the decomposition of the batch materials. This type of furnaces are only a few for the float glass production but this technology is mostly used for small (25 to 100 tonnes/day) and medium (100 to 500 tonnes/day) capacity installations. It can operate continuously between 2 and 7 years. [18]

3.1.3 Cross-fired regenerative furnace powered by Power-to-Gas methane

This process corresponds to the cross-fired regenerative furnace powered by natural gas explained in 2.1.1, with the addition of the Power-to-Gas technology, which delivers renewable gas (r-gas) to the furnace.

PtG technology converts renewable power into gas methane via hydrogen and carbon dioxide [21]. This methanation process is described for the exothermic reaction

$$CO_2 + 2H_2 \rightarrow CH_4 + O_2$$

The installation to generate r-gas explained in the next paragraphs is the model of a PtG methane applied in this thesis.

For the CO_2 capture, air flows through a filter where CO_2 is chemically bound. This filter consists of porous granules mixed with amines. Once the filter is saturated with CO_2, the air supply is interrupted, and the filter is heated to release the CO_2. Afterwards, the air supply is allowed, and the filter is used again. [22, 23]

The hydrogen is obtained from a PEM water electrolysis, which is a cell equipped with a solid polymer electrolyte that conducts the protons, separates the gases and insulates the electrodes. [24]

To get the water for the electrolysis, tap water goes through a reverse osmosis and a electrodeonization to purify. [25]

The chemical methanation 3PM (three phases methanation) is the last step to obtain methane from H_2 combined with CO_2. [26]

The complete process is summarized in the figure 4.

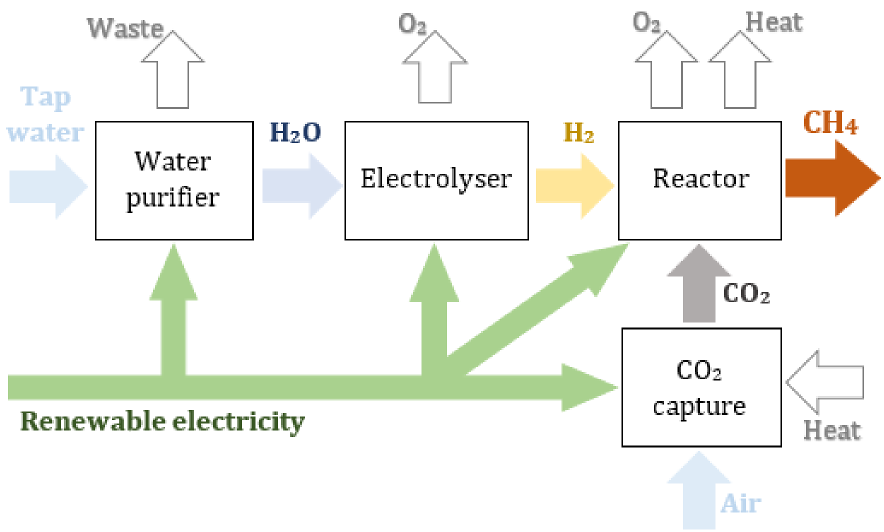


Figure 4 Methanation
Source: own compilation

3.2 Functional unit

The functional unit is a selected measure to which all inputs, outputs and functions of a product system are related to. The main purpose of the functional unit is to provide a reference to ensure comparability of LCA results. It must also be shared for different product systems that are meant to be compared. [10]

The functional unit for this analysis is one tonne float glass cut and ready to be packed and sent. All inputs and outputs are referred to this unit. This functional unit has been chosen because of two reasons:

- There is a huge amount of possibilities for the float glass to be flatted with a specific width and cut with a length and breadth, so it corresponds the necessities of the costumer. Choosing a tonne of glass means no specification regarding the measures of the ribbon. Despite this, a tonne float glass could correspond, for example, to 4 sheets of 0.01m thick 2m width and 5m long float glass [19].
- There is a wide variety of furnace capacities used to form float glass. In the European Union just 1% of the furnaces production is under 400 tonnes a day, the rest are over it until 1100 t/d [18]. The preferred capacity is between 550 and 700 t/d with 48% of the production [18]. As this study does not focus in a certain furnace, the amount of tones produced per day is not specified, as it depends on the furnace capacity.

3.3 System boundary

The system boundary defines the limits of the system analyzed and the processes inside of it. The LCA is completely described within this boundary. To confine the product system, a cut-off criteria defines the inputs which should be considered, and the ones which are irrelevant or not taken into account. The cut-off criteria is also applied for the outputs. The outputs considered should be interesting for the study and remarkable enough to accomplish the goal. This cut-off criteria also explains the reasons of these considerations. [10]

For this thesis the system boundary is defined as follows:

- The Life Cycle starts with the extraction and production of the raw materials used to create float glass.
- The distribution and transportation of the raw materials to the fabric and inside of it is not considered in this study.
- The generation and transportation of the energy used during the process is considered. This includes the production of electricity, natural gas and r-gas.
- The material inputs
- The ancillary material inputs of tin, nitrogen, hydrogen and sulphur dioxide and their evaporation are not regarded due to its small amount and no environmental relevance [18].

- The non-profitable smashed glass in the cutting line is recycled as cullet and taken to the entrance of the furnace mixed with the raw materials. This forms a closed loop in the material flow.
- The production or renovation of machinery and auxiliary elements used during the process (e.g. furnace, containers, refractory bath) is not considered into the Life cycle assessment.
- The recycle or deposit of the machinery and auxiliary elements is not contemplated.
- The LCA ends once the float glass is cooled down and cut, before it is packed to be sent.

The cut-off criteria is applied to mass elements. When an input or output is less than 0,01 kg and corresponds to less than 5% of the mass inputs or outputs of the individual process it is not accounted in the study. Nevertheless, before doing any exclusion, it is checked whether the environmental relevance of the suppressed flow can be considered minor or not.

4 Data collection for the life cycle inventory analysis LCI

In this section, all data and information about the product systems are stated. Besides, each process is detailed and related to the functional unit. In all descriptions, the sources and calculations needed are recorded.

This life cycle assessment is composed of a comparison between a conventional, an electrical and a regenerative with Power-to-Gas systems. A general view of the production process, shared for the three product systems, is shown in Figure 5 .

The production process has been divided in the raw material phase and the manufacture phase. The raw material phase includes the production of the primary raw materials, while the manufacture phase includes the rest of the process in Figure 5 .

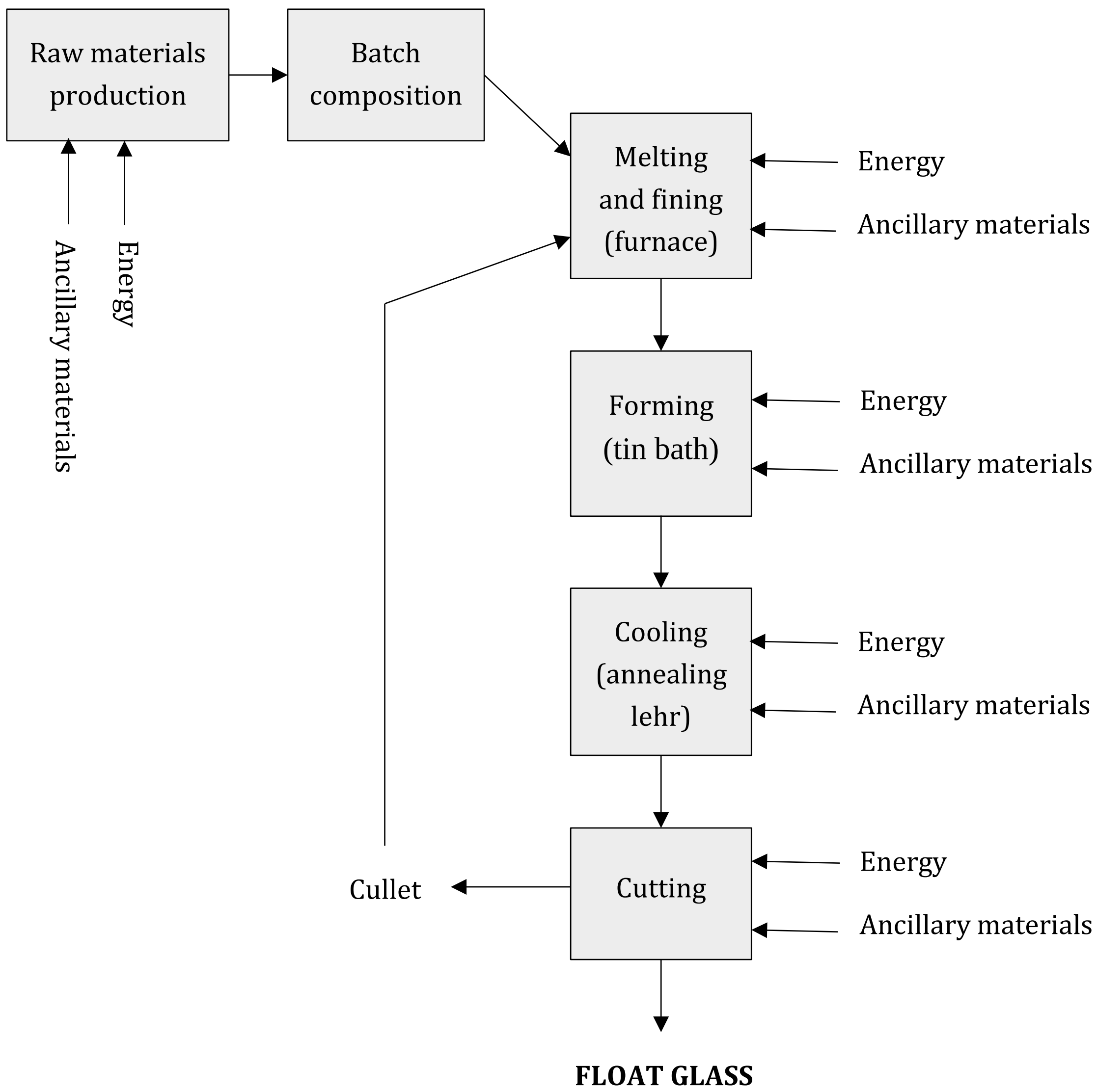


Figure 5 Float glass' production process
Source: own compilation

The raw material phase and the batch composition are the same for the three product systems. For this reason, they are explained first, and separate from the manufacture phase of each.

The inventory analysis of the three product systems have been done with the software "Umberto" [15] and the databases "ecoinvent" [16]. The complete "Umberto" diagrams are shown in the annex A1 -A5.

4.1 Raw material phase

First of all, the raw materials and their percentages are determined. Secondly, the calculations of the energy and materials expenditures are done.

The float glass is generated with a basic soda-lime combination. The called "soda-lime glasses" are the vast majority of industrially produced glasses. They form a large variety of products (e.g. jars, window glass) with a similar composition. [18]

As a soda-lime glass, the principal materials of the float glass are soda and lime. More specifically, for the float glass of this analysis, the components are mixed with the percentages shown in the Table 1. This batch composition is from the literature [18], excluding the minor materials such as colour modifiers and incidental impurities, which are considered null.

Component	Chemical formula	Mass percentage
Silicon dioxide	SiO_2	72,6
Sodium oxide	Na_2O	13,6
Calcium oxide	CaO	8,6
Magnesium oxide	MgO	4,1
Aluminium oxide	Al_2O_3	0,7
Potassium oxide	K_2O	0,3
Sulphur trioxide	SO_3	0,1

Table 1 Float glass raw materials composition
Source [20]

Almost three quarters of the batch composition are silicon dioxide, also known as silica. It is commonly found in nature as quartz (SiO_4). Quartz comprises more than 10% by mass of the earth's crust, which may indicate an easy provision. [27]

The second most present component is sodium oxide, with a 13,6%. It is necessary to low the melting point of the batch, as it acts as a fluxing agent [28]. Sodium oxide (Na_2O) is not found in nature, but it is formed in the furnace from the reaction:

$$Na_2CO_3 \rightarrow Na_2O + CO_2$$

Where Na_2CO_3 is sodium carbonate, known as soda ash and obtained from the heating of soda (sodium carbonate decahydrate $Na_2CO_3 \cdot 10H_2O$), which can be found in nature.

Calcium oxide is commonly known as quicklime and it is obtained by heating calcium carbonate ($CaCO_3$). Calcium carbonate is present in nature as limestone or seashells. Soda-lime glasses are named after both calcium oxide and sodium oxide. The rest of components are a minority. Magnesium oxide (white solid mineral) and aluminium oxide or alumina occur naturally, while potassium oxide must be obtained by heating potassium nitrate (KNO_3), a natural solid source of nitrogen called saltpetre. Sulphur trioxide is a colourless liquid that pollutes significantly while in a gas form, which occurs in air at room temperature and pressure. [29]

The inputs and outputs of each of the individual process are defined for the ecoinvent databases. In the Table 19 of the annex, there are the name and place that define each component.

The co-products, waste, releases to air, ground and soil as well as other environmental aspects are commented in the LCIA.

4.2 Batch composition

To completely describe the raw material phase in "Umberto" [15], all the information need to be related with the functional unit of a tonne of float glass. The raw materials explained in 3.1 are the primary raw materials. Whereas, there is also cullet as secondary raw material. Both primary and secondary materials are mixed together to form the batch, and they are introduced into the furnace. At the end of the manufacture process, the batch is converted to a tonne of float glass and a specific weight of cullet, which returns to the entrance of the furnace.

The manufacturing of float glass, with few exceptional cases, has internal cullet coming from trimmed edges of ribbons, errors and changes. Sometimes it also has external cullet, but many flat glass is mainly recycled for the container glass production, where the quality standards of the final product are not as rigorous as the quality of the flat glass. [18]

The float glass manufacturing uses 10 to 40% of scrap glass to formulate the batch, typically around 20% [18]. This study only considers an internal cullet of 15% of the batch while the raw materials are the 85% remaining. The external cullet is considered zero, because there is no specific information about it in the literature and not all furnaces accept it.

The last thing to take into consideration, before measuring the quantity of primary and secondary raw materials, are the outputs of the process. The outputs of the manufacture are, regarding the mass percentage, 70% finished glass, 10-20% emissions to air and 10-20% cullet [18].

Material inputs	Material outputs
85% raw materials	70% finished glass
	15% emissions to air
15% cullet	15% cullet

Table 2 Mass percentages of glass outputs and respective inputs
Source: own compilation

When the batch warm up, primary and secondary raw materials behave different. The primary raw materials evaporate their dampness, some of them decompose, and the gases trapped in these ones escape. This phenomenon implies a significant decrease of volume and weight (3-20% of mass). The secondary raw materials do not lose any weight. For one tonne of cullet, a tonne of new float glass can be obtained. [18]

Defined a 15% of gaseous emissions and a 15% of cullet, the functional unit of one tonne of float glass represents a 70% of the output. The cullet does not vary its mass in the melting process, so it always represents a 15%. The primary raw materials, though, represents an 85% of the inputs, and they result a 70% of glass and a 15% of gases. Consistently the next equivalence should be respected.

$$\frac{\text{1 tonne float glass}}{\text{70\% output}} = \frac{\text{x tonnes primary raw materials}}{\text{85\% input}}$$

$$\text{x tonnes primary raw materials} = \frac{85}{70} = 1{,}21428\ t$$

A Table 20 with the corresponding quantity for each raw material is in the annex A6.

It is also important to calculate the mass of cullet which will be circulating into the process. Knowing that a 70% of the mass represents the functional unit of 1 tonne of glass, the 15% of cullet should represent a proportional part of this mass.

$$\frac{\text{1 tonne float glass}}{\text{70\% output}} = \frac{\text{x tonnes cullet}}{\text{15\% output}}$$

$$\text{x tonnes cullet} = \frac{15}{70} = 0{,}21428\ tonnes\ cullet$$

4.3 Manufacture phase of the conventional process

The conventional process refers to the float glass manufacture with a cross-fired regenerative furnace. This is the most extended technology for the float glass manufacture nowadays [18].

After defining the inventory for the raw material phase and the principal material input (the batch), the manufacturing can be defined. The Figure 5 displays the manufacture phase of the conventional process.

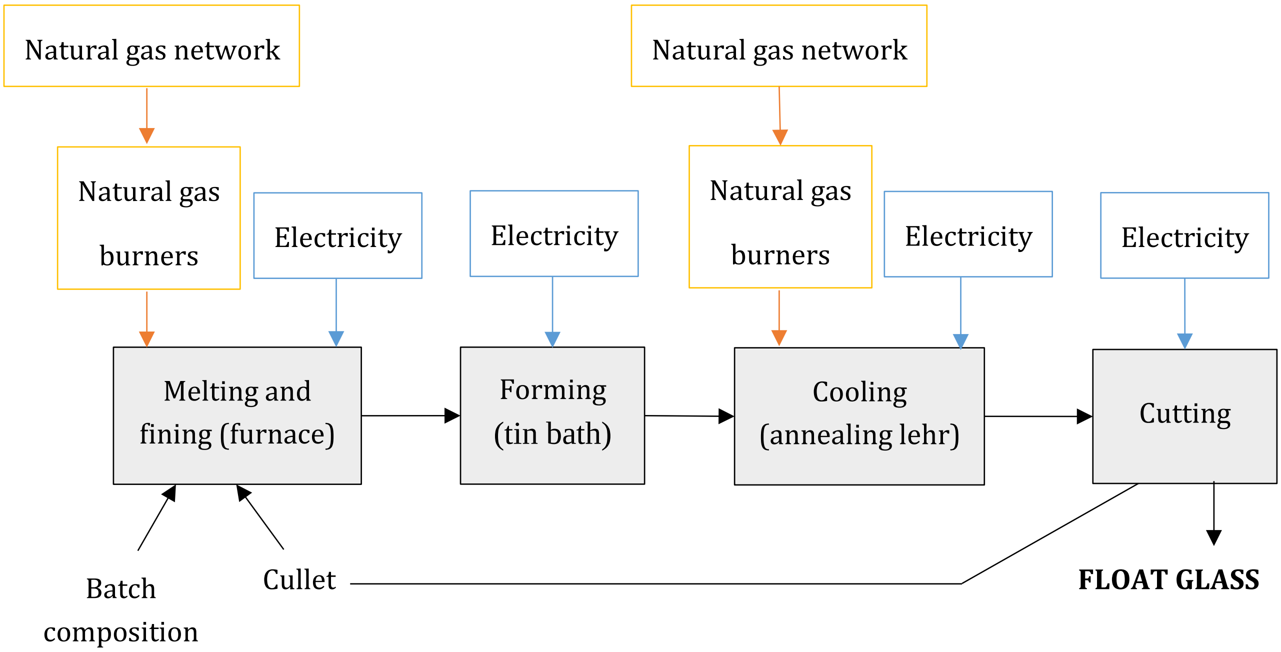


Figure 6 Manufacture phase of the conventional process
Source: own compilation

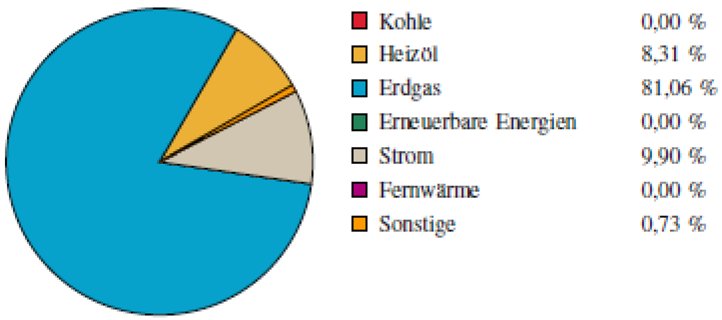
Beginning with the global energy input, the energy consumption of glass production with a cross-fired regenerative furnace is on average 7,5 GJ/tonne glass. The furnace uses the main part of this energy, typically an 83% of it. The forming and the lehr use another 5%, the cutting process 2% and the 10% left is for the control system, the inspection of the product and the lighting and heating of the factory. [18]

Due to the separation made in the process created in "Umberto" [15] and shown in Figure 5, the distribution of this percentage and the energy for each individual process are presented in the next table. The forming and lehr percentage is halved between both processes and the 10% of energy left is shared equally among the four processes.

Process	Percentage of energy (%)	Energy (GJ/tonne glass)
Melting (furnace)	85,5	6,4125
Forming (tin bath)	5	0,375
Annealing (lehr)	5	0,375
Cutting	4,5	0,3375
Total	100	7,5

Table 3 Energy usage distribution of the conventional manufacturing phase
Source: own compilation

The energy of the different processes comes from different sources. The Graphic 1 shows the mean value of the energy sources for 20 enterprises that manufacture flat glass. The results are a predominantly 81% natural gas, a 10% electricity, an 8% fuel oil and a 1% others. [30]



Graphic 2 Energy sources for the manufacture of flat glass
Source [30]

The furnaces are usually firing exclusively natural gas or fuel oil, although some can change from one to the other or even fire them at the same time on different burners [18]. In this thesis, only the firing of natural gas is considered because its environmental impact is smaller than the one of the fuel oil, and the fuel oil is less used.

Apart from the firing, the electrical boost is also used in the furnaces, but it is not specifically considered in this product system. These decisions are made due to three main reasons:

- The dominance of the natural gas as a source of energy for this kind of installations
- The interest to compare this natural gas furnace with a 100% electrical furnace
- The interest to compare this natural gas furnace with a SNG furnace with Power-to-Gas

Following with the energy sources of the production of glass, in the forming process, the tin bath is electrically heated to maintain the molten state of the tin. Whereas, most of the annealing lehrs (over 90%) fire natural gas to cool down the glass gradually enough to remove internal stresses. [31]

With the energy sources defined for each process, the final division of energy sources is shown in the Table 5. When the Table 5 refers to the ancillary energy, it is accounting all the machinery that enable the process, such as the rollers that push the ribbon forward or the control operation system.

Process	Percentage of energy	Energy source
Melting (furnace)	83% heating	Natural gas
	2,5% ancillary energy	Electricity
Forming (tin bath)	5% heating + ancillary energy	Electricity
Annealing (lehr)	2,5% heating	Natural gas
	2,5% ancillary energy	Electricity
Cutting	4,5% cutting + ancillary energy	Electricity

Table 4 Energy sources of the conventional manufacture phase
Source: own compilation

4.3.1 Natural gas burners

The natural gas burners have only natural gas from the network as the input and heat as the output. For this conversion, the lower calorific value of the natural gas is needed. The combustion of natural gas in the furnace or in the annealing lehr only take profit of the transmission of heat of the flame. The exhaust gases contain evaporated water which could be condensed to obtain more energy, but this is not the case.

In the German network, there are natural gas from different countries with different compositions. The one selected is imported from Russia and it is the one with the highest percentage of methane. Its lower calorific value is 37,213MJ/m^3 [32].

Due to the imperfection of the burners, it is not possible to obtain this energy for m^3 natural gas. Therefore, an efficiency of 93% is considered [33]. The energy obtained will then be

$$37{,}213\,\frac{\mathrm{MJ}}{m^3} * \frac{93}{100} = 34{,}608\ MJ/\,m^3$$

4.3.2 Melting and fining

The "melting and fining" activity has seven raw material inputs, a cullet input originated in the cutting activity, the heat input and the electricity input. The quantity of raw materials and cullet related with the functional unit has already been calculated in 3.2 Batch composition. The missing calculation is the heat and the electricity. As it is heating a batch of 1,429 tonnes that will become a molten glass of 1,214 tonnes (instead of 1 tonne molten glass), the energy input is calculated with the energy of the complete manufacture process to obtain a tonne of float glass (7,5GJ), and the percentage of energy used for the furnace (83%).

$$1{,}214 \text{ tonnes glass} * \frac{83}{100} * \frac{7{,}5 \text{ GJ}}{1 \; tonne \; glass} = 7{,}559 \; GJ$$

The electricity input corresponds to the part of electricity consumed to control the operation of the furnace. It is a 2,5% of the total consumption, which correspond to 0,188GJ.

The outputs of the melting and fining process are:

- 1,214 tonnes of molten glass ready to sprout onto the tin surface
- Exhaust gases

The exhaust gases come from the combustion of natural gas and the dissociation of raw material. Only the carbon dioxide is considered because is the exhaust gas with a major environmental impact. Other gases are found in little amounts, do not have an environmental impact or they are usually retained in a filter. The 48,3% of the furnaces had abatement system for oxides of Nitrogen in 2007 in Europe, and a 60,3% had abatement of dust SO_x, HCl, HF and metals. [18]

The emissions of CO_2 from the combustion of natural gas are 0,45kgCO_2/kg glass, while the emissions arisen from the batch are 0,15 kg CO_2/kg glass [34]. The calculations of the outputs of the “melting and fining” activity are

$$0{,}45 \frac{kg \; CO_2}{kg \; glass} * \frac{1000 \; kg \; glass}{1 \; t \; glass} * 1{,}21428 \; t \; glass = \; 546{,}426 \; kg \; CO_2 \; (NG \; combustion)$$

$$0{,}15 \frac{kg \; CO_2}{kg \; glass} * \frac{1000 \; kg \; glass}{1 \; t \; glass} * 1{,}21428 \; t \; glass = \; 182{,}142 \; kg \; CO_2 \; (batch \; dissociation)$$

4.3.3 Tin bath

The molten glass and the electrical energy are the only inputs of the tin bath. As the tin bath consumes a 5% of the total energy, it consumes 0,375GJ/t. This activity enters all inputs and outputs per 1 tonne of float glass, so the output is one tonne of flat glass as well. The tin evaporated is very low and it has no relevant impact [18]. In the process, the renovation of tin is not considered because it is not significant for the study, and the emissions of tin are considered zero.

In order to reduce the oxidation of the tin surface, the atmosphere of this process is reduced by injecting nitrogen and oxygen [18]. These inputs are also not considered since there is no literature and the effects of it are not substantial.

4.3.4 Annealing

The cooling is done in the annealing lehr, which has a 2,5% of electrical energy input (0,188GJ/t), a 2,5% of heating energy input (0,188GJ/t) and a tonne of float glass as input and as an output. The calculation for the energy is the following for both electrical and heat.

$$7{,}5\ \frac{GJ}{tonne\ of\ glass} * \frac{2{,}5}{100} = 0{,}188\ GJ/t$$

In this lehr, sulphur dioxide is sprayed onto the glass surface to protect it from the rollers. The quantity of SO_2 is not included in this LCA, since the emissions are really low and not valued in the literature [18].

4.3.5 Cutting

The last activity in this manufacturing phase is the "cutting". The material input is 1,214 tonnes of float glass and the outputs are 1 tonne of float glass (defined as the reference flow) and 0,214t of cullet. These cullet is directly taken to the "melting and finning" activity.

The electrical energy is a 4,5% of the total, which corresponds to 0,3375 GJ/t, but as it works with 1,214 tonnes, both numbers should be multiplicated to obtain 0,410GJ.

$$7{,}5\ \frac{GJ}{tonne\ of\ glass} * 1{,}214\ t * \frac{4{,}5}{100} = 0{,}410\ GJ$$

4.4 Manufacture phase of the electric-powered process

The electrical process operates only with electricity, which can be regenerative if it is generated for renewable sources. The differences between the electrical and the conventional process are the furnace and the annealing lehr. Both are heated by natural gas burners in the conventional process, while in the electrical process, they are heated with electrodes transmitting heat through electrical resistance.

The most important element of this manufacture phase is the furnace. Just like in the conventional process, the furnace is the facility which consumes more energy and emits more gases.

The electrically-heated furnaces are already used in other glass industries. Many different special and domestic glass furnaces with a small capacity installation (25 to 100t/d) use electric furnaces [18], for example borosilicate and lead glass [35]. These furnaces can also be used with soda-lime glasses, even though it is not extended for the float glass manufacture [35].

A modern electrically-heated furnace could consume 2,88GJ/tonne of glass, but there is no such a furnace yet [36]. A survey conducted in Germany estimated an average of 4,248 GJ/tonne of glass [36]. Compared with the cross-fired regenerative furnace (6,225GJ/t), the electrically-heated furnace consumes a 31% less energy.

Taking into account the theoretical energy requirement of the soda-lime glass without cullet, which is 2,68GJ/tonne [18]:

- The cross-fired regenerative furnace has a 43% efficiency
- The electrically-heated furnace has a 63% efficiency

4.4.1 Melting and fining

The inputs of the electrically-heated furnace are the batch composition (calculated in 4.2) and the energy input calculated below.

$$4{,}248 \frac{GJ}{tonne\ of\ glass} * 1{,}21428\ tonne\ of\ glass = 5{,}158\ GJ$$

The corresponding outputs are 1,214 tonnes of molten glass and the CO_2 from the batch dissociation. The batch emits 0,15kg CO_2 per each kilogram of glass formed [34], which corresponds an output of

$$0{,}15 \frac{kg\ CO_2}{kg\ glass} * \frac{1000\ kg\ glass}{1\ t\ glass} * 1{,}21428\ t\ glass = 182{,}142\ kg\ CO_2$$

4.4.2 Tin bath

The tin bath consumes the same amount of electricity, as it does in the conventional process. It is explained for the conventional process in 4.3.3.

4.4.3 Annealing

The annealing of the ribbon heated by natural gas burners and electrically controlled consumes 0,375GJ/t (calculated for the conventional process in 4.3.4). As there is no reference about the consumption of the electrical annealing lehr, and it is a small part of the total consumption, it is considered that it consumes the same energy, although this energy comes only from electricity.

4.4.4 Cutting

The cutting process consumes the same amount of electricity, as it does in the conventional process. It is explained for the conventional process in 4.3.5.

4.5 Electricity in Germany nowadays and in 2050

The electrical process to produce float glass has been created as a regenerative alternative to the conventional process. When the elements in the process use electricity, there is no combustion and, consequently, no gaseous emissions except for the inherent of the raw materials transformation. Electricity is considered a clean energy, but it is also important to check its origin. If the sources of energy to generate electricity are not renewable, such as coal, then there is a combustion and emission of pollution gases as well.

Because of this, here is a short review of the sources of energy used in Germany to generate electricity.

In 2016, the power generation in Germany came mainly from Lignite (23,1%), hard coal (17,2%), renewable energy (29%), nuclear energy (13%) and natural gas (12,4%) [37]. The 40,3% of power was generated by the combustion of coal, which is a non-renewable and high-polluting source of energy.

Alternatively, the study also focusses in the electricity available in Germany in 2050. Because of the objective to reduce a 95% of the GHG emissions for 2050, the electricity supply system needs to become by then 100% renewable [38].

In order to succeed, the Umweltbundesamt has analysed the potential of the different renewable energies in Germany. The conservative estimation of a technical and ecological potential is the one shown in the Table 5 .

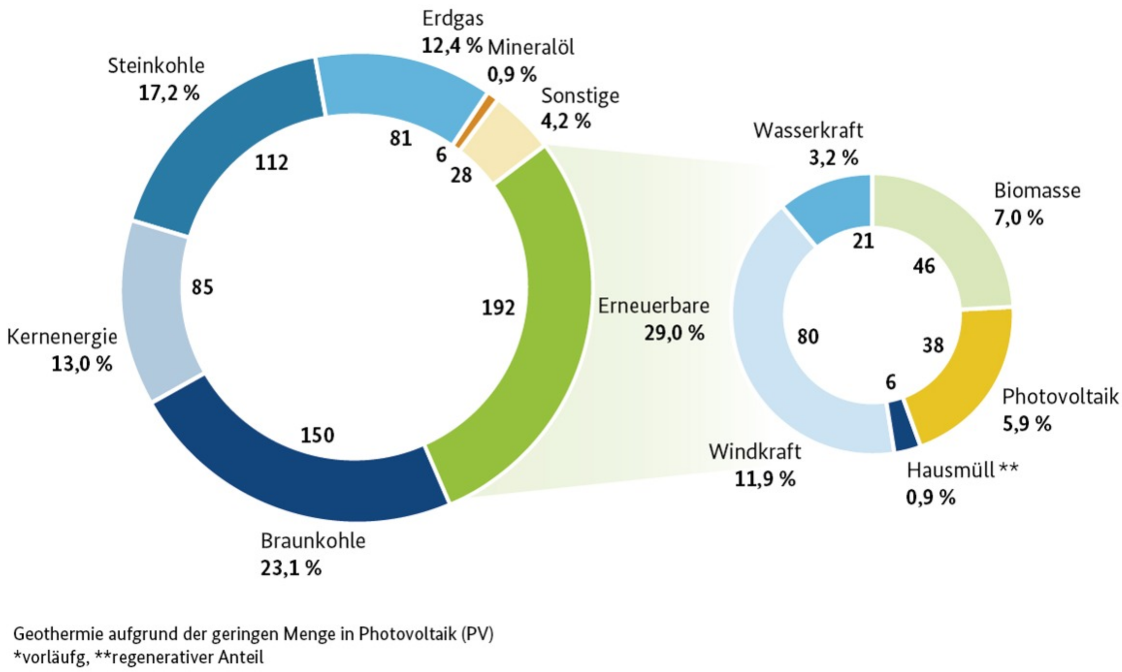


Figure 7 Gross power generation in Germany in 2016 in TWh

Source: [37]

	Technical-ecological potential	Percentage
Photovoltaic	248 TWh	35,18%
On-shore wind energy	180 TWh	25,53%
Off-shore wind energy	180 TWh	25,53%
Hydraulic	24 TWh	3,40%
Geothermic	50 TWh	7,09%
Biomass waste (biogas)	23 TWh	3,26%
Total	705 TWh	100%

Table 5 Renewable energy potential in Germany
Source: own compilation from Umweltbundesamt [38]

In this thesis, the percentage of each potential energy divide from the total is considered the percentage of each source used in the future electrical network in 2050 in Germany.

4.6 Manufacture phase of the r-gas-powered process

The current float glass industries use mainly natural gas to heat up the manufacture process. A regenerative alternative to natural gas could be renewable gas (r-gas) from a Power-to-Gas station. With this alternative, there would be no changes in the infrastructure of the furnace and the annealing lehr. The only addition to the system would be the technologies used to obtain r-gas (water purification, electrolyser, CO_2 absorber and reactor). The r-gas would be directly connected to the natural gas circuit and fired in the burners, the same way that natural gas was.

The electricity provided for PtG is 100% renewable. This is a requirement to produce renewable power methane (RPM) [21].

4.6.1 Water purifier

The first step of the PtG takes place in the water purifier, where a reverse osmosis technology with an efficiency rate of 30% [25] and a electrodeionization with an efficiency rate of 90% [39] remove impurities of tap water to turn it into pure water. The quantity of tap water needed to obtain 1m^3 of pure water is calculated:

$$1m^3\ pure\ water * \frac{100}{30} * \frac{100}{90} = 3{,}704m^3\ tap\ water$$

In order to deliver the required quantity, the time operating with a flow of 20l/h [25] is:

$$1m^3 \ pure \ water * \frac{1000dm^3}{1m^3} * \frac{1l}{1dm^3} * \frac{1h}{20l} = 45{,}45 \ hours$$

Considering a power of 110W, the consumption of electricity is:

$$110W * 45{,}45h * \frac{1kW}{1000W} = 5 \ kWh$$

4.6.2 PEM electrolyser

The electrolyser receives pure water to decompose it and get oxygen and hydrogen gas. The proton exchange membrane electrolyser (PEM electrolyser) chosen is the biggest model from “Areva”, which consumes 4,8 kWh/Nm^3H_2 and have the specific flows shown in the Table 6 [40].

Element	Data sheet flow	Ratio to 1m^3 H_2	Data per 1m^3 H_2
H_2	120m^3 H_2/h	1/120 h	1m^3 H_2
O_2	60m^3 O_2/h	1/12O h	0,5m^3 O_2
H_2O	0,24m^3 H_2O/h	1/120 h	0,002m^3 H_2O

Table 6 Proportions of material flow PEM electrolyser
Source: own compilation from [40]

Because the water (input) and the oxygen (output) should be related to a cubic meter of hydrogen (output), the time in which a cubic meter of hydrogen is obtained, is the same time that needs to flow water and oxygen.

For the electrolyser, the data is entered per 1m^3 H_2 is entered in “Umberto” [15] for this activity. The quantity of O_2 in Umberto is in mass units. To obtain this value, the density of CO_2 is needed [32].

$$0{,}5 \ Nm^3 \ O_2 * \frac{1{,}4290kg}{1 \ Nm^3} = 0{,}7145 \ kgCO_2$$

4.6.3 Carbon dioxide absorber

The CO_2 capturer (or absorber) is described for "Climeworks AG" [22] and it extracts $1Nm^3$ CO_2 from $2600Nm^3$ of air [41]. The output of clean air is $2599Nm^3$. The process uses 0,4kWh of electricity to draw the air into the system and 4,2kWh of heat to extract the CO_2 trapped from the filter [41].

The quantity of CO_2 in "Umberto" [15] is in mass units. To obtain this value, the density of CO_2 is needed [32].

$$1\ Nm^3\ CO_2 * \frac{1{,}9767\ kg}{1\ Nm^3} = 1{,}9767\ kgCO_2$$

4.6.4 Methanation reactor

The methanation is described for the reaction [21]:

$$4H_2 + CO_2 \rightarrow\ CH_4 + 2H_2O$$

A cubic meter of CH_4 could be obtained for a cubic meter of CO_2 and 4 cubic meters of H_2, but as the rate of methanation is 95% [21], the needed amounts of CO_2 and H_2 are calculated as follows:

$$\frac{4\ m^3 H_2}{m^3 CH_4\ teorical} * \frac{1m^3 CH_4\ teorical}{0{,}95m^3 CH_4\ real} = 4{,}21 \frac{m^3 H_2}{m^3 CH_4\ real}$$

$$\frac{1\ m^3 CO_2}{m^3 CH_4\ teorical} * \frac{1m^3 CH_4\ teorical}{0{,}95m^3 CH_4\ real} = 1{,}05 \frac{m^3 CO_2}{m^3 CH_4\ real}$$

As the material flow is described, only the energy input is missing. Knowing the that the conversion rate from electricity to methane can achieve a 78% [24], it is possible to calculate the energy input of the methanation. In this calculation, the low calorific value of the SNC is the one for methane [32].

$$1m^3 SNG * 9{,}971 \frac{kWh\ gas}{m^3 SNG} * \frac{100\ kWh\ electric}{78\ kWh\ gas} = 12{,}783\ kWh\ electric$$

4.7 Definition of "Umberto" product systems

All "Umberto" [15] product systems are divided in raw materials and manufacture phase. The raw material phase is identical for each product system and the four main steps in which the manufacture proceeses ("melting and fining", "tin bath", "annealing" and "cutting") are also in each product system.

The yellow circles without connections are duplicates of the ones, with the same etiquette (e.g. P7 Figure 8 annex A1), that held a previous activity. For instance, the P7 circles represent the receptor of the "natural gas burners" activity output, and the P28 circles represent the receptor of the "market for electricity, medium voltage" activity output or the "energy production in Germany in 2050" activity output, depending on the product system.

4.7.1 Observations of the conventional system

The energy sources for the conventional product system shown in the Figure 8 of the annex A1 are defined in Umberto as follows:

- Electricity is provided by the German market at medium voltage. This activity is defined in the databases ecoinvent and it is used as an input of the processes that need it.
- Natural gas is provided by the German network. The data of this activity is from "ecoinvent" [16]. This includes the energy requirements and the emissions of the high pressure distribution network in Germany, as well as the losses of the networks.

4.7.2 Observations of the electric-powered system

For the electrical-powered product system, there are two "Umberto" diagrams:

- The first one, with the electricity from the network in Germany nowadays shown in figure 9 annex A2 . This system has been created only to verify that its environmental impacts are greater than the ones for the conventional system.
- The second on, and regarded in this thesis, with the electricity generated in Germany in 2050 from renewable sources (figure 10 annex A3).

The "energy production in 2050 in Germany" activity has a double square because it represents a subnet. This subnet is shown in the figure 11 of the annex A4 and it is compose for the proportionally distributed renewable energy sources explained in 4.5. The P10 circle of the subnet corresponds to the P28 circle of the principal net. All subnet inputs are aggregated to the net activity input, as well as all the subnet outputs are aggregated to the net activity input.

All the different sources send "electricity, high voltage" (geothermal, wind energy, biogas and hydro) or "electricity, low voltage" (photovoltaic) to the middle activity "T2" with the indicated quantity on the table 11. Every electricity production activity are part of the databases ecoinvent. The inputs and outputs of each energy production are collected in the inputs and outputs of the "electricity in Germany in 2050". The output of "T2" is 705 TWh and it is called "electricity 2050". P10 is connected to each activity of the manufacture process of glass delivering "electricity 2050" with the quantities already calculated.

4.7.3 Observations of the r-gas-powered system

For the electrolyser, the data is enetered per $1m^3$ H_2 is entered in "Umberto" [15] for this activity. The quantity of O_2 in Umberto is in mass units. To obtain this value, the density of CO_2 is needed [32].

$$0{,}5\ Nm^3\ O_2 * \frac{1{,}4290kg}{1\ Nm^3} = 0{,}7145\ kgCO_2$$

The quantity of CO_2 in "Umberto" [15] is in mass units. To obtain this value, the density of CO_2 is needed [32].

$$1\ Nm^3\ CO_2 * \frac{1{,}9767\ kg}{1\ Nm^3} = 1{,}9767\ kgCO_2$$

5 The life cycle inventory analysis LCI

The LCI collects the data for every input and output of the product system referred to the functional unit. These data are detailed for each individual process, and they can be classified and calculated to extract relevant information.

The electricity in 2050 defined in "Umberto" [15] with the different renewable sources does not fit into the criteria stablished in the scope. This issue is due to the non-renewable inventory and impacts that are described for the renewable energy sources by the "ecoinvent" databases [16]. In order to fell into the scope, the renewable energies have to be considered in the long-term operation, as they require no non-renewable sources and they do not have emissions that contribute to the global warming. This consideration is obtained by subtracting the fossil, nuclear and primary forest material or energy inputs corresponding to the electricity in 2050.

5.1 Cumulative energy demand CED methodology

For the energy classification of the LCI, the cumulative energy demand (CED) is calculated. The CED is described by the Verein Deutscher Inginieur [17] as "the sum of cumulative energy demands for the production, for the use and for the disposal of the economic good.". The entire demand is valued as primary energy.

In this study, only the cumulative energy demand for production is summed. Nevertheless, this cumulative energy demand is divided into non-renewable and renewable CED. The subcategories fossil, nuclear and primary forest compose the non-renewable CED while solar, wind, water, biomass and, geothermal compose the renewable CED.

The CED is calculated using the "ecoinvent" databases [16]. Therefore, the specifications applied are collected in the *ecoinvent report No. 3* [42].

5.2 Cumulative raw material demand CRD methodology

For the material classification, the cumulative raw material demand (CRD) is calculated. The CRD is described for the model of the Verein Deutscher Inginieur [43] and it separates the materials for different categories. In this study, the CRD can be energetic or non-energetic. In the non-energetic, there are the subdivisions: metallic mineral, non-metallic mineral, rock, gas or water. This division is made manually and respecting the cut-off criteria, which is 0,01kg or 0,01m^3. The only material with a lower quantity considered is the uranium, due to its high energy contribution. The minerals with a metallic percentage lower than 25% are classified as non-metallic mineral, except the ones that are named as a metal.

All the material values are included in kg. The materials which quantities were expressed in volume has been converted to mass using the densities:

- Natural gas density: 0,783 kg/m^3 CH_4 [32]
- Water density: 1000 kg/m^3 H_2O

- Wood approximate density: 600 kg/m^3 wood
- Air density: 1,225kg/m^3

5.3 Results for the conventional system

This chapter collects the aggregate inventory inputs of the raw material and manufacture phase of the conventional production system. The inventory has been obtained from the “Umberto” [15] model described in 4.7 and calculated for the functional unit of one tonne of float glass.

5.3.1 Cumulative energy demand CED

As the conventional production is powered by natural gas and electricity from the network in Germany, the energy sources are mainly non-renewable. Nevertheless, the electricity derives from a mix of renewable and non-renewable sources. In the following tables, it is possible to recognise the CED for every process and every non-renewable resource, and the global CED for every renewable resource.

The CED non-renewable fossil represents the bigger cumulative energy demand of the conventional process. In it, the electricity market takes the greatest part with 2713 MJ-eq. The nuclear CED is almost eleven times smaller than the fossil CED. The primary forest CED is almost null.

	CED non-renewable		
	fossil (MJ-eq)	nuclear (MJ-eq)	primary forest (MJ-eq)
sulfur trioxide production [RER]	14,7	2,1	0,001
potassium nitrate production [RER]	54,4	2,0	0,003
magnesium oxide production [RER]	76,0	44,2	0,012
aluminium oxide production [GLO]	123,1	4,4	0,004
silica sand production [DE]	285,2	26,5	0,055
quicklime production [CH]	484,3	39,6	0,008
soda production [RER]	717,9	127,5	0,200
market for electricity [DE]	2713,4	970,6	0,542
market for natural gas [DE]	10918,8	182,5	0,085
Total each (MJ-eq)	15387,7	1399,5	0,910
Total (MJ-eq)	16788,1		

Table 7 CED non-renewable of the conventional process

The CED renewable is not significant in front of the non-renewable results. Almost the complete amount of these cumulative energy demands is originated from the electricity network. The major energy demand is biomass and it comes from the electricity market.

CED renewable	MJ-eq
Solar	0,1
Water	212,4
Wind	138,7
Biomass	389,9
Geothermal	2,0
Total	743,1

Table 8 CED renewable of the conventional process

<table>
<tr><td rowspan="8">CED conventional system 17531,2 MJ-eq</td><td rowspan="3">non-renewable 16788,1 MJ-eq</td><td>fossil</td><td>15387,7</td></tr>
<tr><td>nuclear</td><td>1399,5</td></tr>
<tr><td>primary forest</td><td>0,91</td></tr>
<tr><td rowspan="5">renewable 743,1 MJ-eq</td><td>solar</td><td>0,1</td></tr>
<tr><td>water</td><td>212,4</td></tr>
<tr><td>wind</td><td>138,7</td></tr>
<tr><td>biomass</td><td>389,9</td></tr>
<tr><td>geothermal</td><td>2,0</td></tr>
</table>

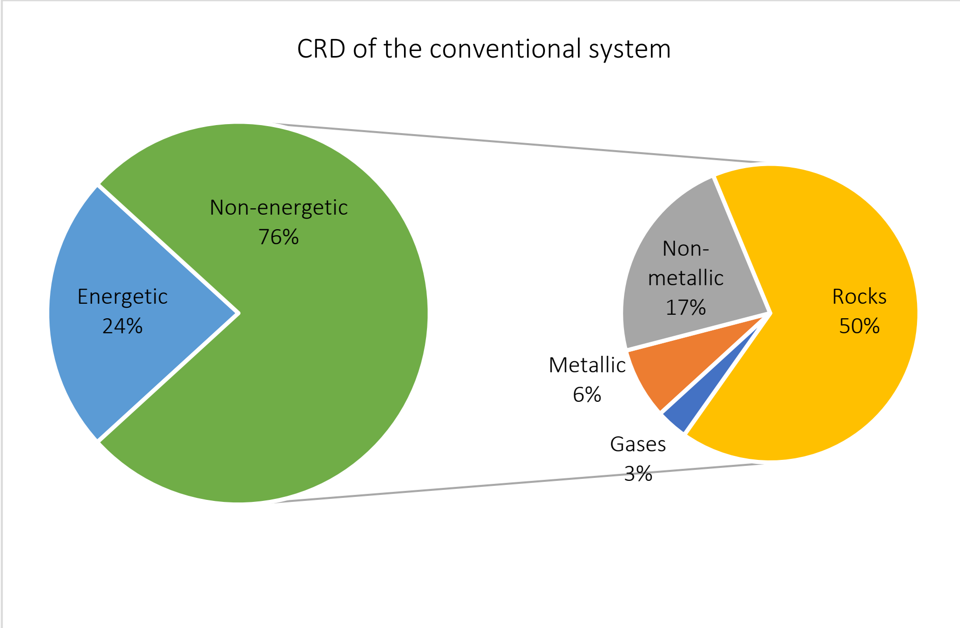
Table 9 CED of the conventional process

The total CED for the conventional process is 17531,2 MJ-eq. About 88% of this CED is fossil.

5.3.2 Cumulative raw material demand CRD

The cumulative raw material demand of all the materials of the conventional process is shown in the annex A7. This CRD demonstrates a great utilization of fossil raw materials, with 230 kg natural gas and 222 kg of coal (brown and hard). The uranium is also present, with 0,0025 kg. These raw materials are added to the energetic CRD.

The CRD major content are the non-energetic materials with, among others, 1070 kg of rocks (65% of the non-energetic). The partition of CRD of the conventional process is shown in the Graphic 3.



Graphic 3 CRD of the conventional system

The cumulative raw material demand of water has been considered apart because its mass reaches 1808 tonnes. More than a 90% of this water is used in turbines.

5.4 Results for the electric-powered system

This chapter collects the aggregate inventory inputs of the raw material and manufacture phase of the electric-powered system. The inventory has been obtained from the "Umberto" [15] product system described in 4.7 and calculated for the functional unit of one tonne of float glass.

5.4.1 Cumulative energy demand CED

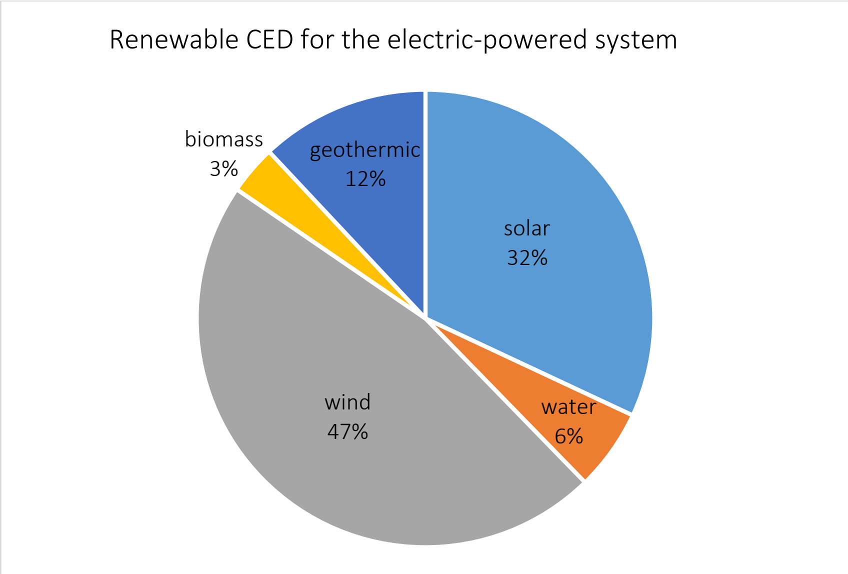
The electric-powered system uses only electricity from renewable energies in the manufacture phase and almost only non-renewable energies in the raw material production.

Due to this consideration, the non-renewable CED arises from the raw materials production. The greater demand of non-renewable CED is from the soda production with a fossil CED of 717,87 MJ-eq.

CED non-renewable	**MJ-eq**
Fossil	1755,50
Nuclear	246,38
Primary forest	0,28
Total	**2002,16**

Table 10 CED non-renewable of the electric-powered system

For the renewable CED, the main contributor of each source is the electricity used in the manufacture phase. As the percentages of the electricity mix has been described in 4.5, this renewable CED has approximately the same proportions.



Graphic 4 Renewable CED for the electric-powered system

The total cumulative energy demand is 9680,03 MJ-eq, a 79% of which arises from renewable energy sources.

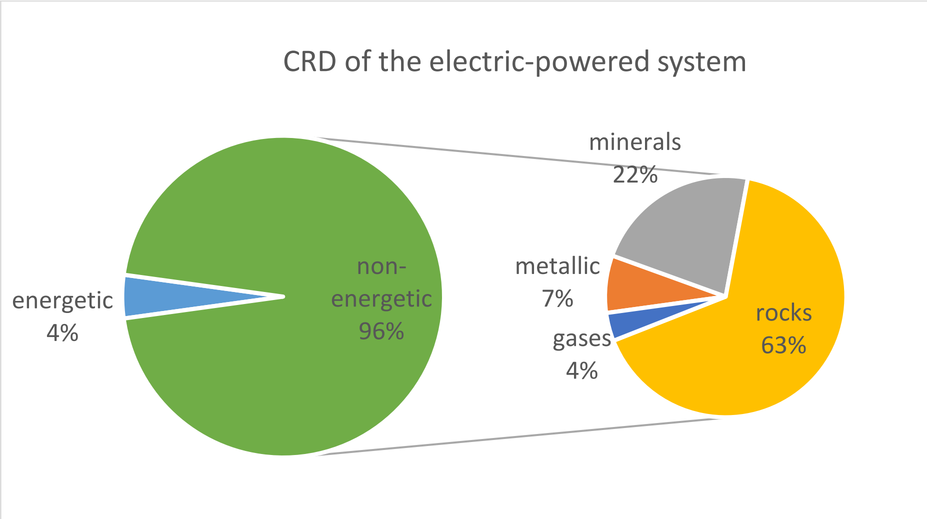
CED electric-powered system **9671,09 MJ-eq**	non-renewable 2002,20 MJ-eq	fossil	1755,50
		nuclear	246,38
		primary forest	0,28
	renewable 7668,89 MJ-eq	solar	2454,11
		water	441,62
		wind	3596,40
		biomass	256,57
		geothermal	920,18

Table 11 Global CED electric-powered system

5.4.2 Cumulative raw material demand CRD

The cumulative raw material demand of the electric-powered process is shown in the annex A8. The CRD is devided into the energetic and non-energetic. For this process, the energetic raw materials used are only the ones for the raw material production, which is 75,59 kg. The uranium is present in the raw material phase with a 0,00045 kg.

The CRD major content though, are the non-energetic materials, with 1070 kg of rocks (65% of the non-energetic, 63% of the total). The partition of CRD of the conventional process is shown in the Graphic 5.



Graphic 5 CRD of the electric-powered system

The cumulative raw material demand has been separated as its mass is 30 tonnes. The main part of it is used for cooling (21 tonnes).

5.5 Results for the r-gas-powered system

This chapter collects the aggregate inventory inputs of the raw material and manufacture phase of the r-gas-powered system. The inventory has been obtained from the "Umberto" [15] product system described in 4.7 and calculated for the functional unit of one tonne of float glass.

5.5.1 Cumulative energy demand CED

The r-gas-powered system is considered a regenerative process from gate to gate, which indicates that the non-renewable CED can only arise from the raw material production. This characteristic is shared with the electric-powered system. Therefore, their non-renewable CED is the same, and it is indicated in the Table 11.

The renewable cumulative energy demand is shown in the table 12. In the annex A9 there is a table for the renewable CED of each process.

CED renewable	MJ-eq
Solar	11333,77
Water	1768,31
Wind	16579,38
Biomass	447,87
Geothermal	4245,90
Total	**34375,23**

Table 12 CED renewable r-gas-powered system

5.5.2 Cumulative raw material demand CRD

The cumulative raw material demand of the r-gas-powered system is shown in the annex A10. In the CRD energetic category, the raw materials aggregated are all from the raw material production, which is 75,59 kg. The uranium mass is 0,00045 kg.

The CRD major content is located in the non-energetic category, where the air used for the CO_2 absorber (approximately 606500m^3) is added. The total amount of each category and the main contributors state in the table 13.

<table>
<tr><th colspan="2"></th><th>Total (kg)</th><th>Main contributor</th><th>% contribution</th></tr>
<tr><td colspan="2">Energetic</td><td>75,59</td><td>Coal, hard</td><td>38,90</td></tr>
<tr><td rowspan="4">Non-energetic</td><td>metallic minerals</td><td>156,14</td><td>Magnesite</td><td>72,59</td></tr>
<tr><td>non-metallic minerals</td><td>408,60</td><td>Calcite</td><td>73,30</td></tr>
<tr><td>rocks</td><td>1303,38</td><td>Gravel</td><td>90,63</td></tr>
<tr><td>gases</td><td>743151,58</td><td>Air</td><td>99,97</td></tr>
<tr><td colspan="2">Water</td><td>18982727,97</td><td>Water, turbine use</td><td>99,68</td></tr>
</table>

Table 13 CRD of the r-gas-powered system

6 The life cycle impact assessment LCIA

The aim of the LCIA is to assign determined data from the life cycle inventory to impact categories. To do so, the data of the LCI has to be calculated for the indicator values of the impact category. An indicator value is, for example, "kg CO_2-eq", which may correspond to kg of CO_2 or kg of CO (among others) and define the impact category of global warming potential.

The classification of the LCI data (assignment to impact category) and its characterisation (calculation of the indicator value) is calculated by the software "Umberto" [15]. These results are exposed for the raw material phase and the three production phases (conventional, electric-powered and r-gas-powered) related to the functional unit of one tonne glass.

In this study, the LCIA is set to calculate the global warming potential, the ozone, water and fossil depletion and the terrestrial acidification of the manufacture of float glass.

	Unit	**Indicator result**
Global warming potential	kg CO_2-eq	277,50
Fossil depletion	kg oil	41,83
Terrestrial acidification	kg SO_2-eq	1,13
Water depletion	m^3 water	0,36
Ozone depletion	CFC-115-eq	1,8203E-05

Table 14 Raw material phase

	Unit	**Indicator result**
Global warming potential	kg CO_2-eq	1088,78
Fossil depletion	kg oil	324,880937
Terrestrial acidification	kg SO_2-eq	0,9781472
Water depletion	m^3 water	1,46316318
Ozone depletion	CFC-115-eq	0,00012424

Table 15 Manufacture phase of the conventional system

	Unit	Indicator result
Global warming potential	kg CO_2-eq	182,142
Fossil depletion	kg oil	0
Terrestrial acidification	kg SO_2-eq	0,57329816
Water depletion	m^3 water	0,49168322
Ozone depletion	CFC-115-eq	1,472E-05

Table 16Manufacture phase of the electric-powered system

	Unit	Indicator result
Global warming potential	kg CO_2-eq	182,142
Fossil depletion	kg oil	0
Terrestrial acidification	kg SO_2-eq	2,64770408
Water depletion	m^3 water	2,27968446
Ozone depletion	CFC-115-eq	6,7985E-05

Table 17 Manufacture phase of the r-gas-powered system

7 The life cycle interpretation LCI

The life cycle interpretation combines the data collected in the life cycle inventory analysis and in the impact assessment to evaluate the product systems.

In this chapter the evaluations of the raw material phase, the conventional production system, the electric-powered production system and the r-gas-powered production system are made. Afterwards, these production systems are compared to reach conclusions.

7.1 Evaluation of the raw material phase

In the raw material phase, the processes with the most meaningful impacts are the soda and quicklime production. Even though they are not the main raw material for float glass (silica sand), they account between a 65% and a 74% of the total indicator value, with the first two highest indicator values for every impact category. For example, the largest global warming potential contribution process is the quicklime production with a 42% of the total, while the second largest contribution comes from the soda production with a 23% of the total. The silica sand production is the third greatest part for four of the five impact categories evaluated.

In relation to the GWP, the life cycle inventory data correspond to the indicator values of the impact category. For example, the quicklime production has an output of 115 kg carbon dioxide in the LCIA that, with other little contributions, reaches the 117 kg CO_2-eq of the indicator value.

Related to the GHG emissions, it is also helpful to know the fossil depletion. In this raw material phase, it is mainly caused by soda, quicklime and silica production (with a 40%, 27% and 16% respectively). This impact is related to the fossil usages, which arise in the soda and quicklime production from the combustion fossil fuels. In both soda and quicklime production, the raw materials found in nature are heated up to liberate the carbon dioxide, evaporate water and obtain soda or quicklime.

Regarding the terrestrial acidification, the emissions of SO_2, NO_x and NH_3 are taken into account. The activity which emits the greatest amount of these gases is the production of soda. In the LCIA outputs, the release of sulphur dioxide is the greatest from these group, but ammonia (NH_3) and nitrogen oxides (NO_x) are also present. The LCIA data and the indicator value correspond for the raw material processes.

Another impact category is the water depletion. It is defined in the LCIA methodology to consider water from lakes, rivers, wells and unspecified natural source. Nevertheless, it has been noticed that the water from unspecified natural source is not added to the indicator value. The aggregated value of "water, unspecified natural source" materials of the LCIA inputs could take a significant role in the indicator value of water depletion.

The last evaluation alludes to the ozone depletion. This value indicator is under the cut off criteria, which implies that the data used to calculate it is out of the cut off criteria as well. Even if it is a small value indicator, it has been calculated thanks to the "Umberto" program [15]. The inventory data is diverse, but it is comprised for a range of values congruent with the value indicator.

7.2 Evaluation of the conventional production system

The activities regarded in this production system are mainly define with their consumption of natural gas and electricity. Therefore, the most important activities, which originate the impacts, are the production and transportation of electricity and natural gas, which amounts rely on the consumption.

The global warming potential arises predominantly from the combustion of natural gas in the furnace. The amount of CO_2 calculated in the inventory is 546 kg CO_2 and match with the amount considered in the impact assessment. The production and transportation of electricity and NG are also analysed, and the different GHG emissions are correctly characterised and added in their indicator values.

The fossil, ozone and water depletion and the terrestrial acidification are completely defined by the natural gas and electricity production and transportation processes. An 80% of the fossil depletion is caused by the "natural gas" activity, while the other 20% comes from the "electricity". This percentages are not because of the resources extracted, but because of the global percentage of natural gas (85,5%) and electricity (14,5%) utilization. Like the fossil depletion, the ozone depletion arises from the "natural gas" activity an 86% and from the "electricity" activity the 14% left.

For the terrestrial acidification, the electricity activity has a greater impact than the natural gas activity. Nevertheless, for the defined consumptions, the natural gas activity contributes a 62% to the indicator value and the electricity activity a 38%.

For the water depletion, the 82% of the indicator value comes from the "natural gas" activity. This activity has water from wells, rivers, lakes, and an unspecified natural source. These data are added in the indicator value, in exception for the water with unspecified natural source. In this case, though, the "unspecified" water has not a remarkable value, so the total would not change significantly, if it was added. The rest of the indicator value for the water depletion coming from the "electricity" activity is entirely added.

7.3 Evaluation of the electric-powered production system

The electric-powered production system, has only a principal process, which is the electricity generation. This electricity from renewable sources explained in 4.5 is a single activity connected to the four steps of the manufacture process in order to deliver the corresponding energy to each one.

The global warming potential is null for the electricity generation, but there are 182 kg of CO_2 from the gaseous emissions, which the raw materials released in the melting tank when they are heated up. This emission is accounted in the LCIA inventory as well as in the GWP indicator value.

Because of the assumptions regarded in the scope of this project, the fossil depletion is null.

Regarding the terrestrial acidification and the ozone depletion, the pertinent data of the LCIA is coherent to the results of the indicator values.

The water depletion, as well as in the other production systems, does not include the LCIA data of water from unspecified natural origin in the indicator value, although it is included in the LCI methodology of this impact category. In this case, it could make a substantial difference on the indicator value.

7.4 Evaluation of the r-gas-powered production system

Considering that the r-gas-powered production system has the same structure and installation as the conventional system, the principal processes are also the electricity and the natural gas generation and transport (in this case renewable gas and electricity from renewable sources).

Thanks to the addition of the Power-to-Gas installation and the supply of electricity from renewable energies, the power of this production system is free of GHG emissions. The only emission considered in the GWP is the gaseous emission of the batch. For the same reason, the fossil depletion is also zero.

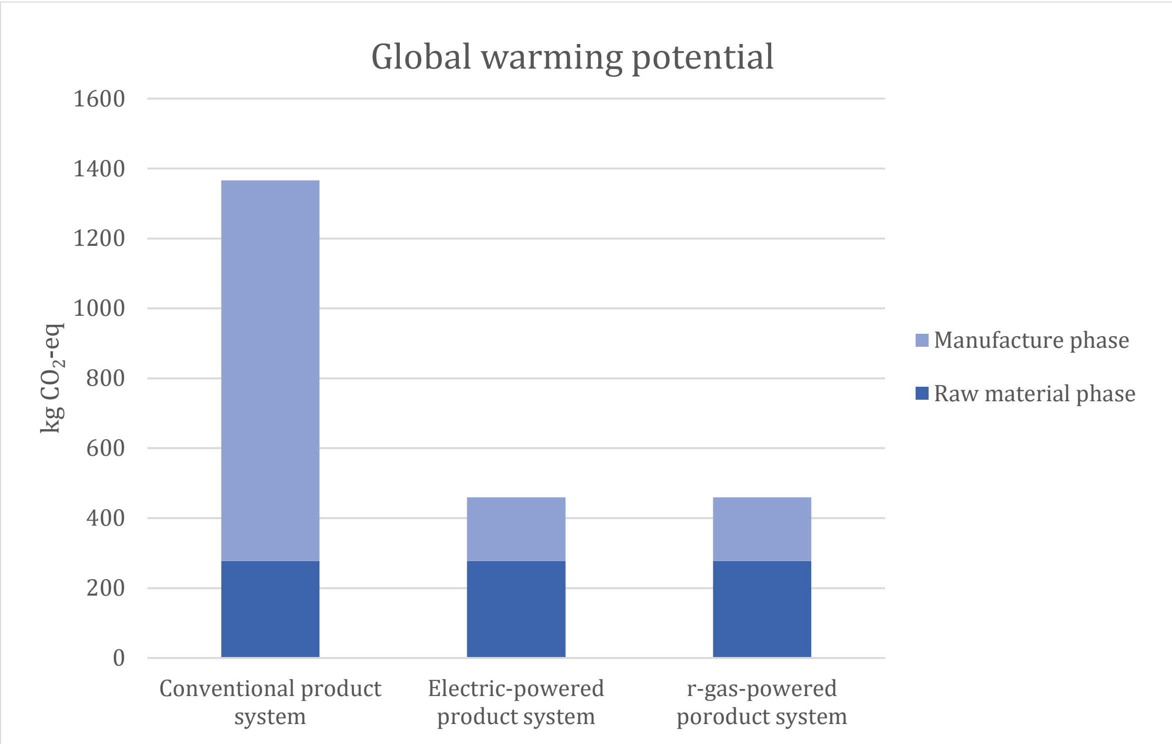
As the Power-to-Gas installation is powered by electricity and the material inputs are only air and tap water, the LCI has calculated the indicator values considering all the information is originated from the "electricity" activity and the "water purifier" activity.

The comprehensiveness of the classification and characterization has been checked for the five impact categories with success, except for the water depletion. As in the other production systems, the water from an unspecified natural source, is not taken into account, even though it is considered in the methodology of this category impact.

7.5 Comparison between production systems

This life cycle assessment has been done with the objective to compare the nowadays float glass production with two possible regenerative production systems. This chapter presents first the comparison of the GWP between the three production systems, and secondly, the comparison of the conventional process results with an LCA of flat glass made for a company.

In the LCIA chapter, the category impacts have been calculated for the raw material and for the manufacture phase separately. The graphic below show the aggregated amount of the phases for the global warming potential. The graphics for the three product systems comparing the fossil, ozone and water depletion and the terrestrial acidification are shown in the annex A11.



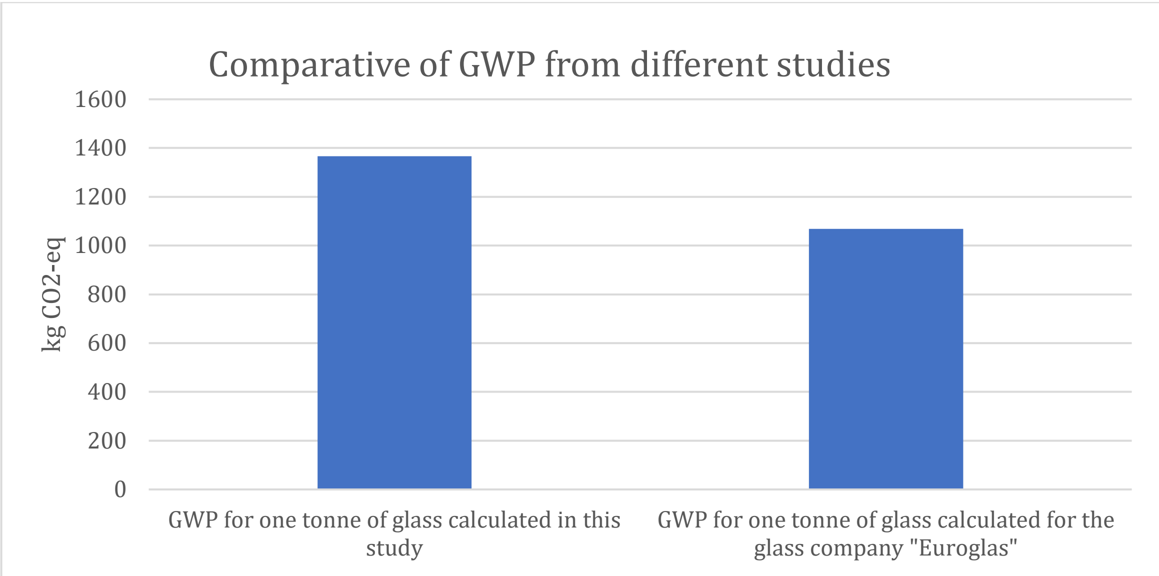
Graphic 6 Global warming potential

The graphic above shows the comparison between the kilograms of CO_2 equivalent emissions of the three production systems presented in this thesis. The difference between the conventional and the regenerative is significant, while both electric-powered and r-gas-powered product systems have the same amount.

Focusing first in the regenerative product systems, they do not accomplish the emission of 0 GHG. The graphic shows that, the raw material phase, which has not been studied to become regenerative, accounts a great quantity of CO_2 equivalent. Moreover, once the raw materials form the batch and enter the furnace, they liberate carbon dioxide as they heat up. This gaseous emission is inherent to the formation of glass and it is account the total amount of CO_2 equivalent for the manufacture phase.

Concerning the conventional product system, the same raw material phase is assumed, but in this case the spotlight would be the manufacture phase. In it, the furnace consumes at least three quarters of the total energy demand, and with this energy consumption, the combustion of fossil fuel and its emissions.

Thanks to a published LCA of the float glass done by the company "ift" for "Euroglas" [43], the comparison of the GWP for the conventional process is possible. The data given in the LCA is regarding a functional unit of 1 m^2 float glass of 1 mm thickness. Knowing the density of 2500 kg/m^3, this corresponds to 2,5 kg [19]. The result of the indicator value could change because of the change of the functional unit, but this is just considered for an approximative comparation.



Graphic 7 Comparative of GWP from different studies

The graphic shows this study obtained a quite approximated result, even though it is higher than the LCA done with the collected data of a real operative production system.

8 Critical reflection

The critical reflection is first done for the methods and, afterwards for the results.

For this thesis, the products systems considered are mainly described with energy inputs, while the material data are vaguely contemplated due to the lack of literature. The only and most important input materials added are the emissions for the combustion of natural gas or e-gas in the furnace, and the gaseous emissions from the decomposition of the raw materials.

The fact that the “ReCiPe” is randomly selected among some other possible in the “umberto” software [15], may be considered, as well as the selection of impact categories (except for the principles GWP, CED and CRD) that are chosen following an approximation from the example of the LCA calculated by “ift” [43].

The results are affected for the missing data of the manufacture process, which may arise a lower water depletion indicator value, because the use of water in the system has not been account. Another influence can be made by the missing data related to the gases that are used or scape from the system, which may also arise a lower terrestrial acidification,

The last critical reflection is the concert about the “ecoinvent” [16] data of an activity, which have been eliminated or not considered because their presences are contrary to the defined scope (for example the electricity model created with renewables energies in which “ecoinvent” [16] data has fossil inputs), may have originated dishonest results.

9 Outlook

- A different batch may be difficult to find, although the percentages of each raw material may vary and influence a little the environmental impacts. Another option to lw the emissions from the raw material phase could be a different raw material supply (e.g. from plants nearby, or with less consume of fossil fuels).
- It is easy for electricity to become regenerative because the energy is easy to substitute, but the material usage is quite hard to change.
- A different electricity composition based in the nowadays renewable energy generation for power electricity. (not production of electricity decentralize for house use) could be analysed for increasing the electric-furnaces before 2050.
- The installation of the furnace and their life should be analysed in detail, and if the energy needed could come nowadays from r-energy.
- The float furnaces nowadays pretend to have bigger capacities to improve the efficiency of the natural gas by reducing the heat loses. By the cold-top electric furnace, it is not necessary, with a higher efficient

10 Summary

In this thesis, a life cycle assessment has been developed to assess some environmental impacts of the manufacture of float glass in a comparison way between a conventional process powered by natural gas (with a cross-fired regenerative furnace), an electric-powered process (with resistive heating and renewable energy) and a renewable-gas-powered process (with a Power-to-Gas technology).

Each model has been described accurately and calculated from cradle to gate with the functional unit of tonne of float glass and the same raw material phase. Some of the remarkable results are the fossil cumulative energy demand, which arises 16788 MJ-eq for the conventional process and 2002 MJ-eq for the electric-powered process.

The cumulative raw material demand has been calculated as well, originating results of 76 kg of energetic CRD from the electric-powered and the renewable-gas-powered, which represents only a 4% of the total CRD of these processes; in front of 500 kg from the conventional process, which stand for a 31% of the total CRD of this process.

In the LCIA, the global warming potential has been accounted with an impact category of 1360 kg CO_2-eq for the conventional process, and 460 kg CO_2-eq for the regenerative processes, where the 100% of it is due to the raw material phase emissions or the inherent gaseous emission from the batch. The table 18 show these indicator values.

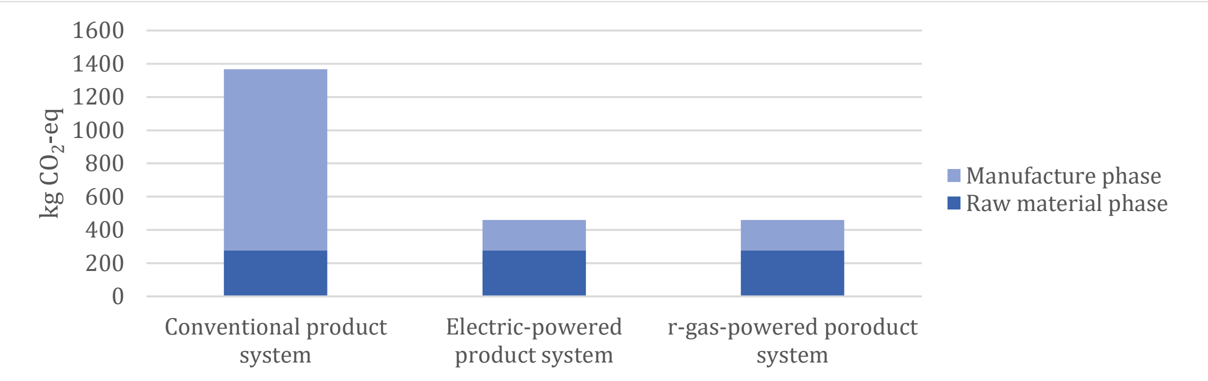


Table 18 GWP

This work could be improved, taking into consideration the modification of the production of the raw materials. Even if it is easier to change energy rather than materials, the consideration of a extraction and production of raw materials with renewable energies and in within short distances to the manufacture.

The collection of more information about the material inputs and outputs, could define more precisely the impact categories of water depletion or terrestrial acidification.

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A. Annex

A1 “Umberto” conventional diagram

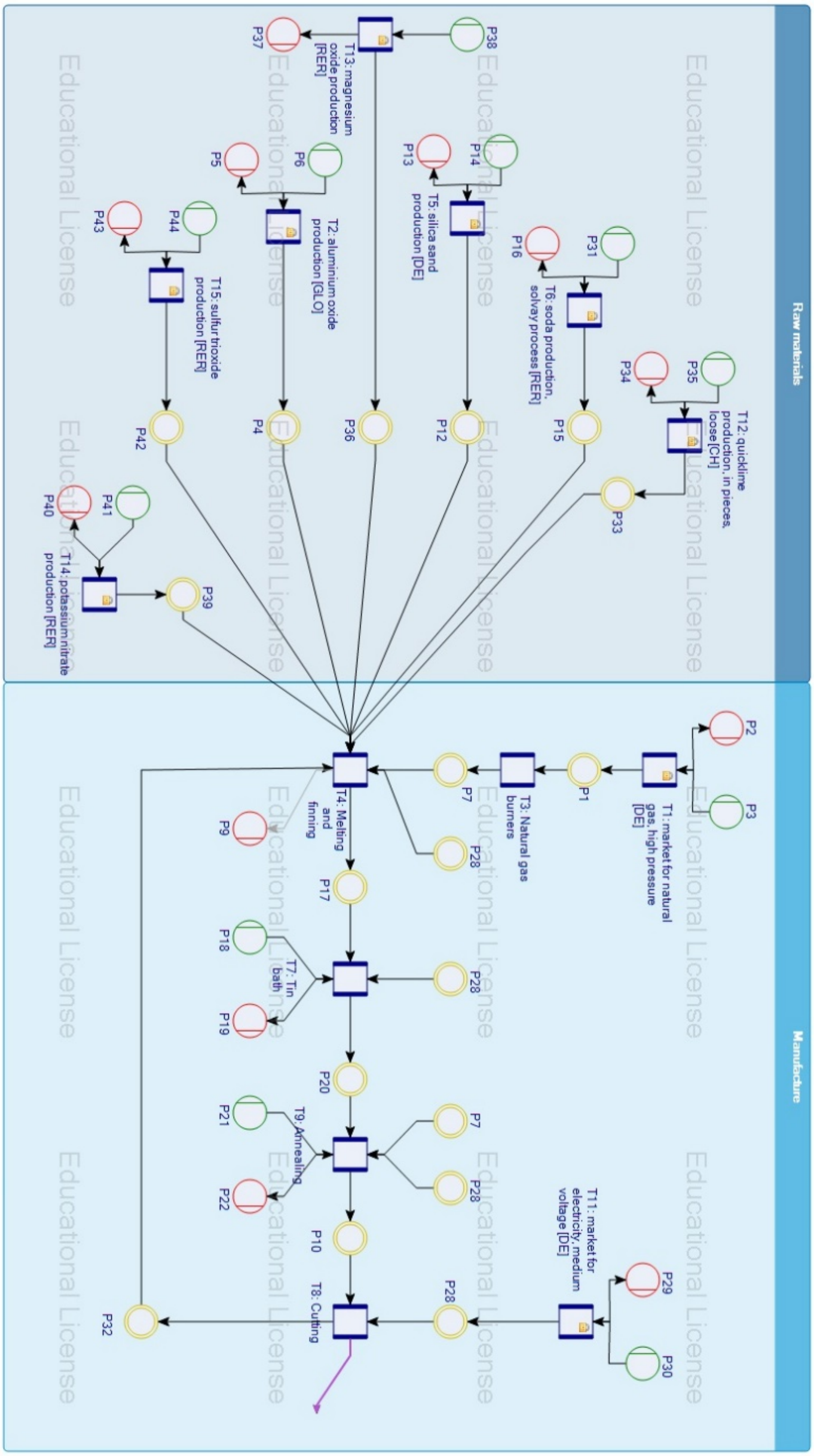


Figure 8 Conventional diagram

A2 “Umberto” electric-powered diagrams

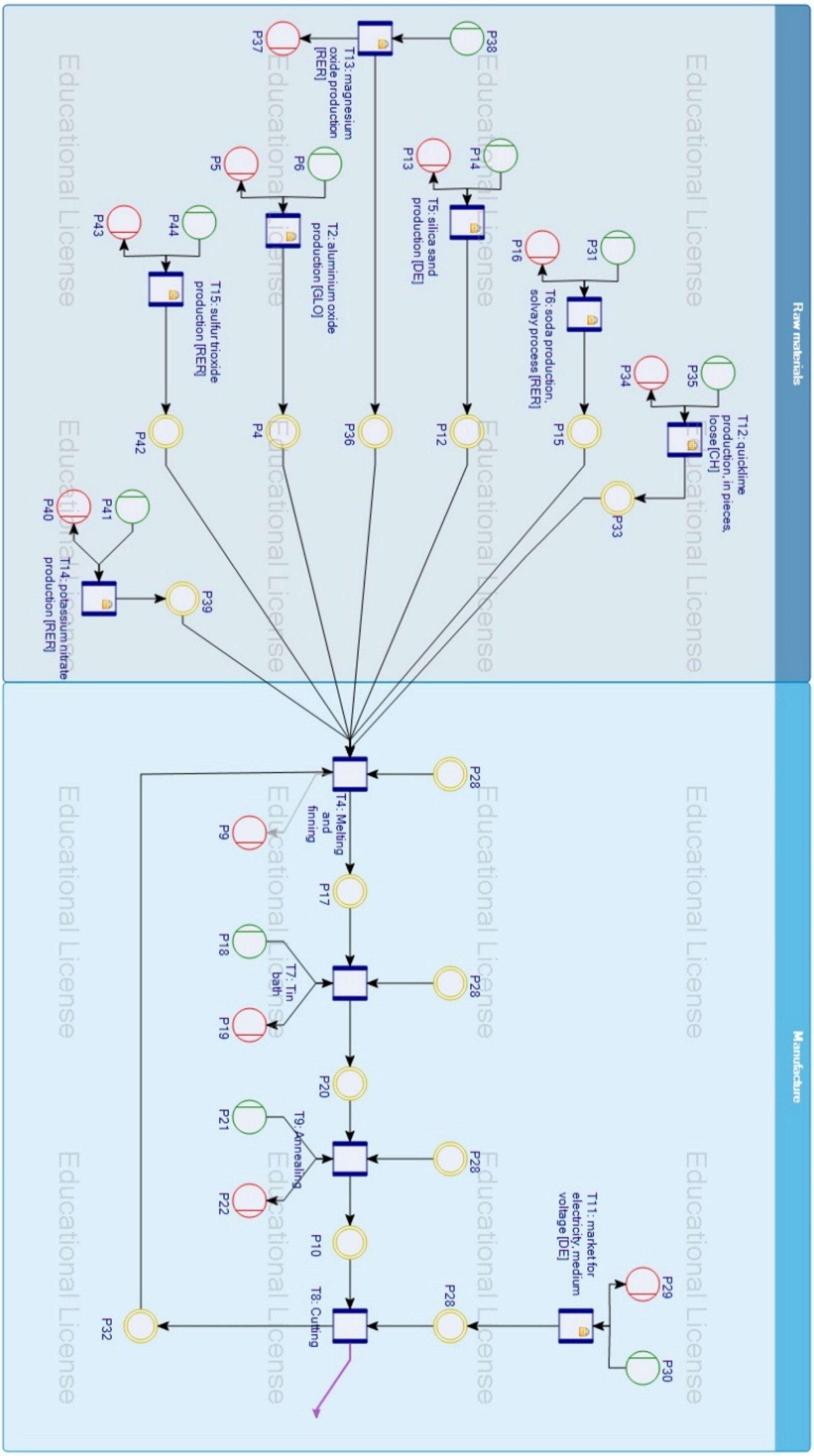


Figure 9 Electric-powered non-renewable diagram

A3 “Umberto” electric-powered diagram in 2050

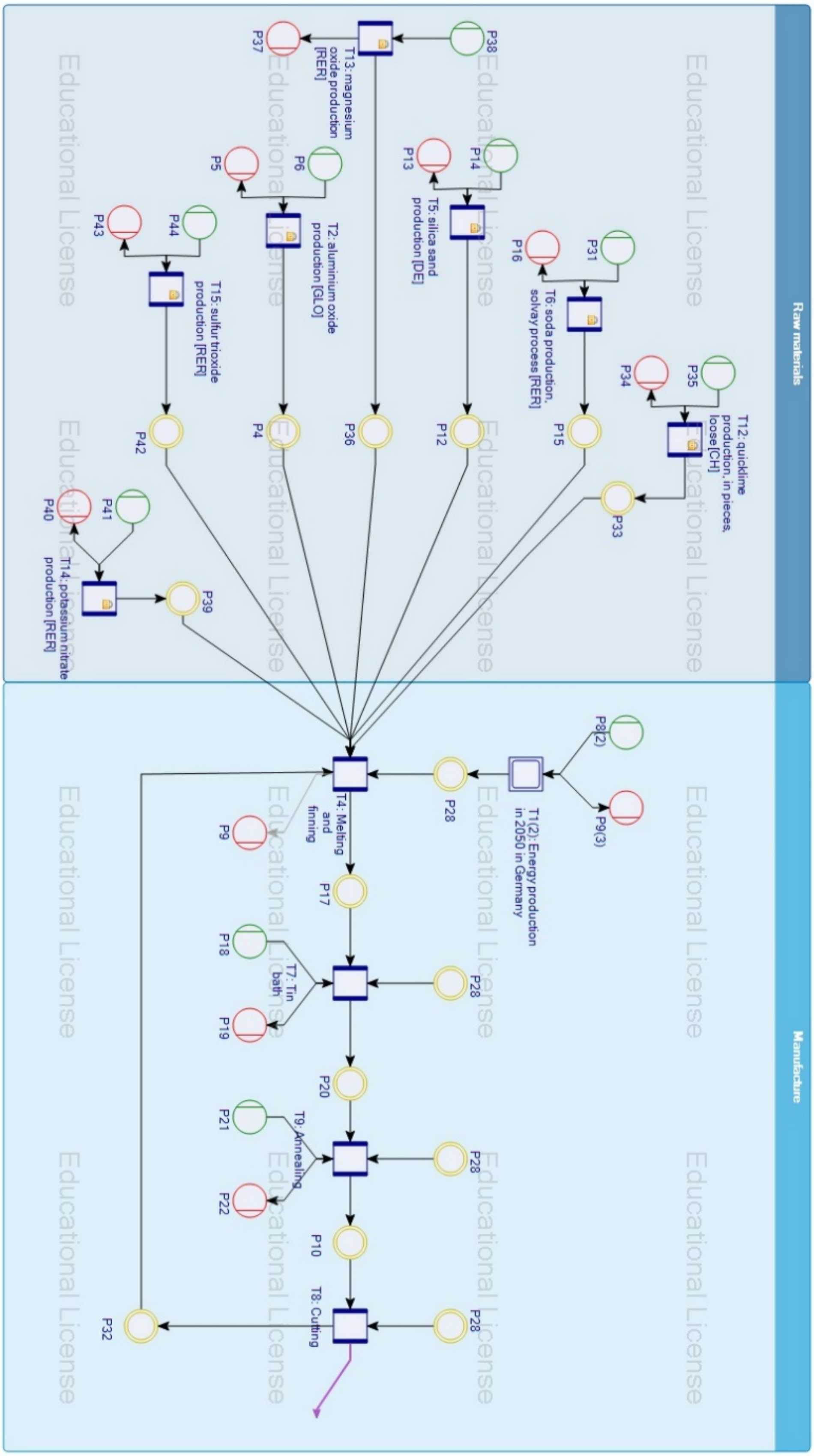


Figure 10 Electric-powered diagram in 2050

A4 "Umberto" electricity mix in 2050

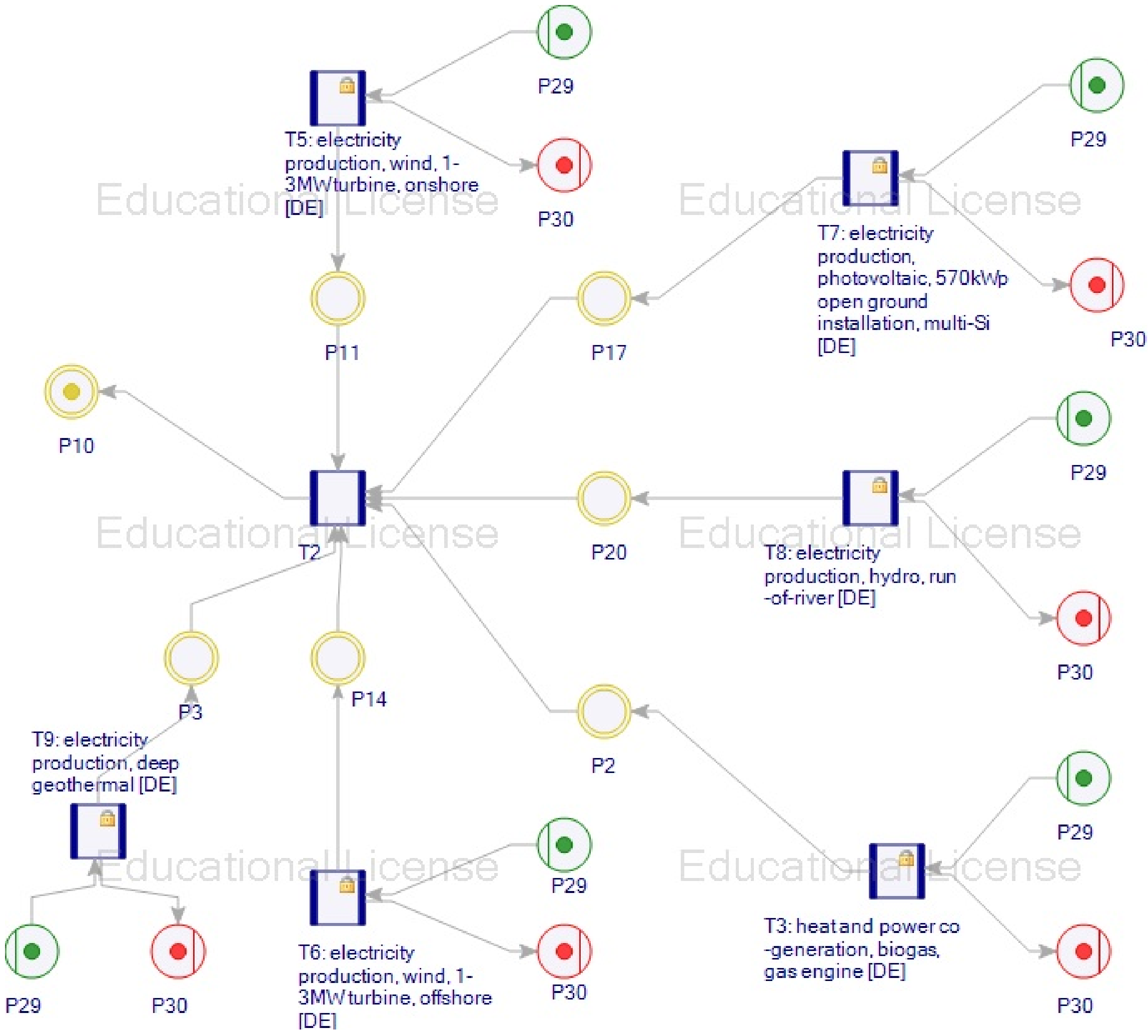


Figure 11 Electricity in 2050

A5 “Umberto” r-gas-powered diagram

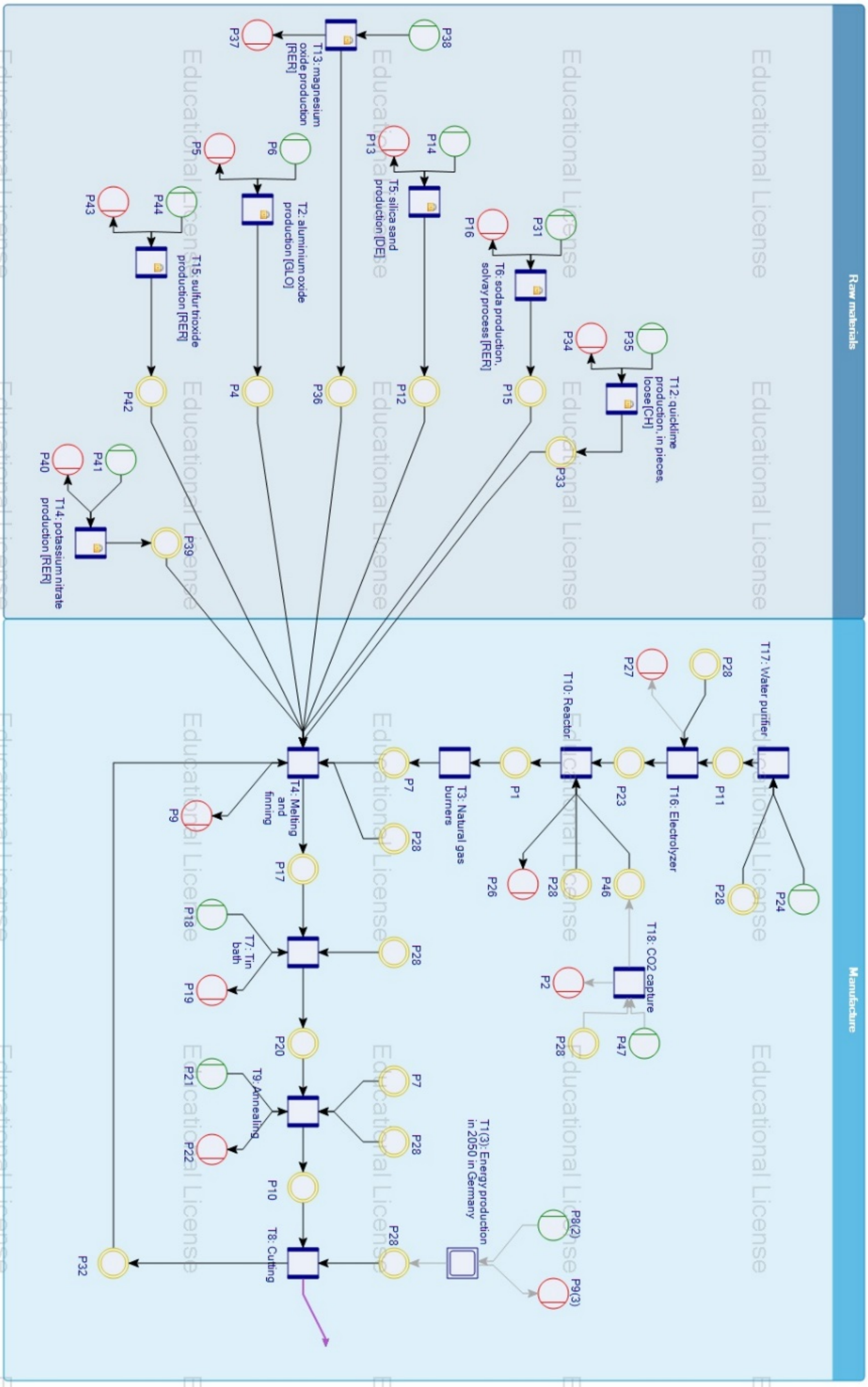


Figure 12 R-gas-powered system diagram

A6 Batch composition in "ecoinvent" databases

Component	Process in ecoinvent	Produced in
Silicon dioxide (SiO_2)	silica sand, production	DE (Germany)
Sodium oxide (Na_2O)	soda production, solvay process	RER (Europe)
Calcium oxide (CaO)	quicklime production, in pieces, loose	CH (Switzerland)
Magnesium oxide (MgO)	magnesium oxide production	RER (Europe)
Aluminium oxide (Al_2O_3)	aluminium oxide production	GLO (Globe)
Potassium oxide (K_2O)	potassium nitrate production	RER (Europe)
Sulphur trioxide (SO_3)	sulfur trioxide production	RER (Europe)

Table 19 Raw material production processes from ecoinvent
Source: own compilation

The data was search for the production in Germany. When these were not available, data from Switzerland, Europe or the Globe has been selected.

Component	Mass percentage (%)	Mass needed (kg)
Silicon dioxide (SiO_2)	72,6	881,57
Sodium oxide (Na_2O)	13,6	165,14
Calcium oxide (CaO)	8,6	104,43
Magnesium oxide (MgO)	4,1	49,79
Aluminium oxide (Al_2O_3)	0,7	8,5
Potassium oxide (K_2O)	0,3	3,64
Sulphur trioxide (SO_3)	0,1	1,21
Total	100	1214,28

Table 20 Calculation of raw material mass inputs

Source: own compilation in ecoinvent

A7 Cumulative raw material demand of the conventional process

		material inputs	value (kg)
energetic (499,13kg)		Carbon, organic	0,04
		Coal, brown	135,17
		Coal, hard, unspecified	87,41
		Gas, natural	229,03
		Gas, mine	0,90
		Oil, crude	24,69
		Peat	0,28
		Wood, soft	11,57
		Wood, hard	10,04
		Uranium	0,0025
non-energetic (1619,72kg)	metallic minerals (125,41kg)	Aluminium, in ground	5,38
		Chromium, 25.5% in chromite	0,10
		Copper, 0.52% in sulfide	0,02
		Copper, 0.59% in sulfide	0,01
		Copper, 0.99% in sulfide	0,03
		Copper, 1.18% in sulfide	0,02
		Copper, Cu 0.38%	0,03
		Iron, 46% in ore	6,62
		Lead, 5.0% in sulfide	0,02
		Magnesite, 60% in crude ore	113,06
		Manganese, 35.7% in sedimentary deposit	0,02
		Nickel, 1.98% in silicates	0,06
		Zinc, 9.0% in sulfide	0,03
	non-metallic minerals (369,04kg)	Barite, 15% in crude ore	0,38
		Calcite	268,44
		Dolomite	0,15
		Fluorspar	0,02
		Gypsum	0,10
		Kaolinite, 24% in crude ore	0,01
		Phosphorus, 18% in apatite	0,02
		Sodium chloride	96,83
		Sylvite, 25 % in sylvinite	3,03
		TiO2, 54% in ilmenite	0,01
		Vermiculite	0,05
	rocks (1069,77kg)	Basalt	0,16
		Clay, bentonite	0,14
		Clay, unspecified	4,03
		Gangue, bauxite	57,17
		Gravel	1008,07
		Pumice	0,14
		Shale	0,05
		Argon-40	0,01

	gases (55,50kg)	Carbon dioxide, in air	41,47
		Nitrogen	0,55
		Oxygen	13,47
water (1808535kg)		Water, cooling	43207,25
		Water, lake	7,84
		Water, river	1132,58
		Water, salt, ocean	93,52
		Water, salt, sole	15,45
		Water, turbine use	1760652,72
		Water, unspecified	2748,57
		Water, well	6

Table 21 Cumulative raw material demand of the conventional process

A8 Cumulative raw material demand of the electric-powered process

		material	**value (kg)**
energetic (75,59kg)		Coal, hard, unspecified	29,40
		Oil, crude	19,26
		Coal, brown	8,35
		Peat, in ground	0,17
		Carbon, organic	0,01
		Gas, natural	4,42
		Gas, mine	0,23
		Wood, soft	7,74
		Wood, hard	6,01
		Uranium	0,00045
non-energetic (1661,95kg)	metallic minerals (128,05kg)	Magnesite, 60% in crude ore	113,10
		Iron, 46% in ore	7,61
		Aluminium	6,41
		Chromium, 25.5% in chromite	0,25
		Nickel, 1.98% in silicates	0,15
		Zinc, 9.0% in sulfide	0,12
		Copper, Cu 0.38%	0,08
		Lead, 5.0% in sulfide	0,07
		Manganese, 35.7% in sedimentary deposit	0,07
		Copper, 0.99% in sulfide	0,06
		Copper, 0.52% in sulfide	0,04
		Copper, 1.18% in sulfide	0,04
		Copper, 0.59% in sulfide	0,03
		Copper, 2.19% in sulfide	0,02

		Zinc, Zn 0.63%	0,01
	non-metallic minerals (372,66kg)	Calcite	270,71
		Sodium chloride	98,07
		Sylvite, 25 % in sylvinite	3,05
		Dolomite	0,25
		Gypsum	0,22
		Barite, 15% in crude ore	0,17
		Fluorspar, 92%	0,07
		Carnallite	0,03
		Vermiculite	0,03
		Kaolinite, 24% in crude ore	0,02
		TiO2, 54% in ilmenite	0,02
		Phosphorus, 18% in apatite	0,01
	rocks (1098,30kg)	Gravel	1024,50
		Gangue, bauxite	68,04
		Clay, unspecified	5,25
		Clay, bentonite	0,16
		Basalt	0,12
		Pumice	0,09
		Sand, unspecified	0,07
		Metamorphous rock, graphite containing	0,03
		Shale	0,03
	gases (62,94kg)	Oxygen	42,41
		Carbon dioxide	18,59
		Nitrogen	1,90
		Argon-40	0,04
water (30183,34kg)		Water, turbine use	4608,63
		Water, cooling	21813,57
		Water, unspecified natural origin	2832,86
		Water, river	582,24
		Water, well	258,14
		Water, salt, ocean	73,54
		Water, salt, sole	14,36

Table 22 Cumulative raw material demand of the electric-powered process

A9 Cumulative energy demand of the r-gas-powered process

	Solar (MJ-eq)	Water (MJ-eq)	Wind (MJ-eq)	Biomass (MJ-eq)	Geothermal (MJ-eq)
sulfur trioxide production [RER]	0,00	0,50	0,12	0,51	0,01
potassium nitrate production [RER]	0,00	0,90	0,09	1,06	0,02
aluminium oxide production [GLO]	0,00	1,98	0,27	1,17	0,06
silica sand production [DE]	0,01	3,92	0,60	42,77	0,10
magnesium oxide production [RER]	0,00	6,80	2,50	7,86	0,21
quicklime production [CH]	0,00	27,35	0,39	1,29	0,02
soda production [RER]	0,02	33,51	4,32	149,04	0,64
Electricity in 2050 in Germany	11333,73	1693,34	16571,09	244,16	4244,85
Total (MJ-eq)	**11333,77**	**1768,30**	**16579,38**	**447,87**	**4245,90**

Table 23Cumulative energy demand of the r-gas-powered process

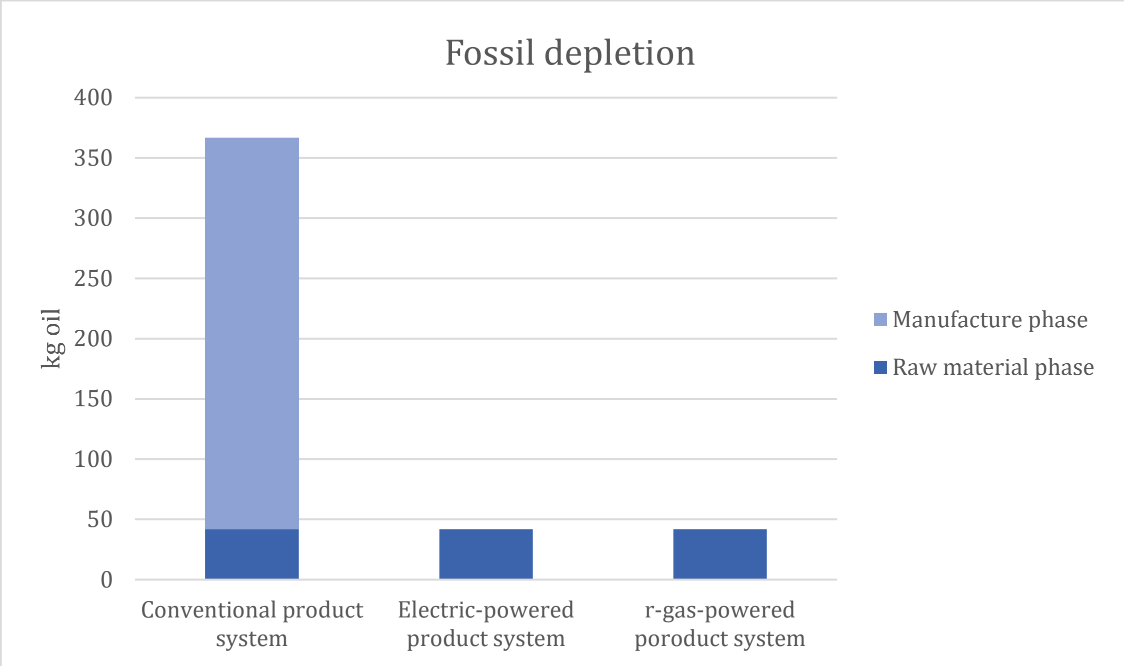
A10 Cumulative raw material demand of the r-gas-powered process

		material	**value (kg)**
energetic (75,59kg)		Coal, hard	29,40
		Coal, brown	8,35
		Oil, crude	19,26
		Gas, natural	4,42
		Gas, mine	0,23
		Peat	0,17
		Carbon, organic	0,01
		Wood, soft	7,74
		Wood, hard	6,01
		Uranium	0,00045
non-energetic (745019,71kg)	metallic minerals (156,14kg)	Magnesite, 60% in crude ore	113,34
		Iron, 46% in ore	29,12
		Aluminium	10,24
		Chromium, 25.5% in chromite	0,88
		Nickel, 1.98% in silicates	0,55
		Zinc, 9.0% in sulfide	0,48
		Zinc, Zn 0.63%, in mixed ore	0,05
		Lead, 5.0% in sulfide	0,27
		Lead, Pb 0.014%, in mixed ore	0,04
		Manganese, 35.7% in sedimentary deposit	0,27
		Nickel, 1.13% in sulfid	0,01
		Copper, Cu 0.38%, in mixed ore	0,29
		Copper, 0.97% in sulfide	0,03

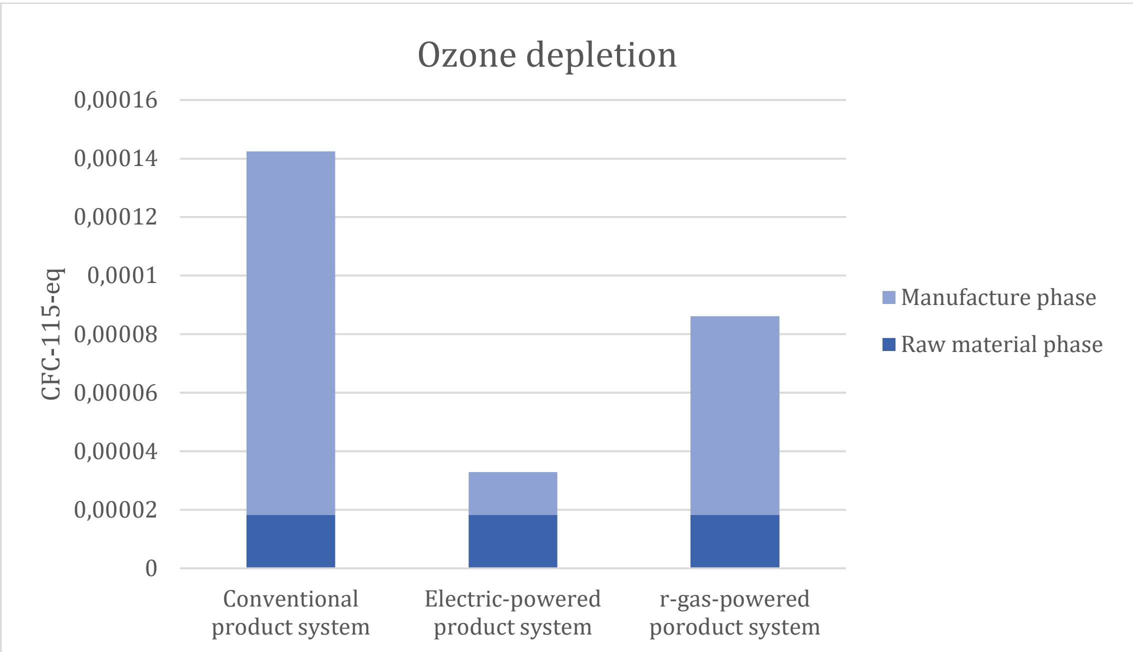
		Copper, 1.42% in sulfide	0,02
		Copper, 2.19% in sulfide	0,05
		Copper, 0.99% in sulfide	0,18
		Copper, 0.52% in sulfide	0,14
		Copper, 1.18% in sulfide	0,12
		Copper, 0.59% in sulfide	0,09
	non-metallic minerals (408,61kg)	Calcite	299,49
		Sodium chloride	103,29
		Sylvite, 25 % in sylvinite	3,23
		Dolomite	1,02
		Gypsum	0,83
		Barite, 15% in crude ore	0,50
		Kaolinite, 24% in crude ore	0,08
		Vermiculite	0,06
		TiO2, 54% in ilmenite	0,06
		Phosphorus, 18% in apatite	0,03
		Phosphorus, 18% in apatite	0,02
	rocks (1303,38kg)	Gravel	1181,30
		Gangue, bauxite	108,79
		Clay, unspecified	11,81
		Clay, bentonite	0,61
		Sand, unspecified	0,32
		Basalt	0,26
		Pumice	0,18
		Shale	0,10
	gases (743151,58kg)	Oxygen	189,90
		Nitrogen	7,89
		air	742935,05
		Carbon dioxide, in air	18,59
		Argon-40	0,15
water (18982727,97kg)		tap water	7,60
		Water, turbine use	18921855,64
		Water, cooling	54424,30
		Water, unspecified	3643,56
		Water, river	1927,18
		Water, well	681,43
		Water, salt, ocean	148,57
		Water, salt, sole	23,94
		Water, lake	15,75

Table 24 Cumulative raw material demand of the r-gas-powered process

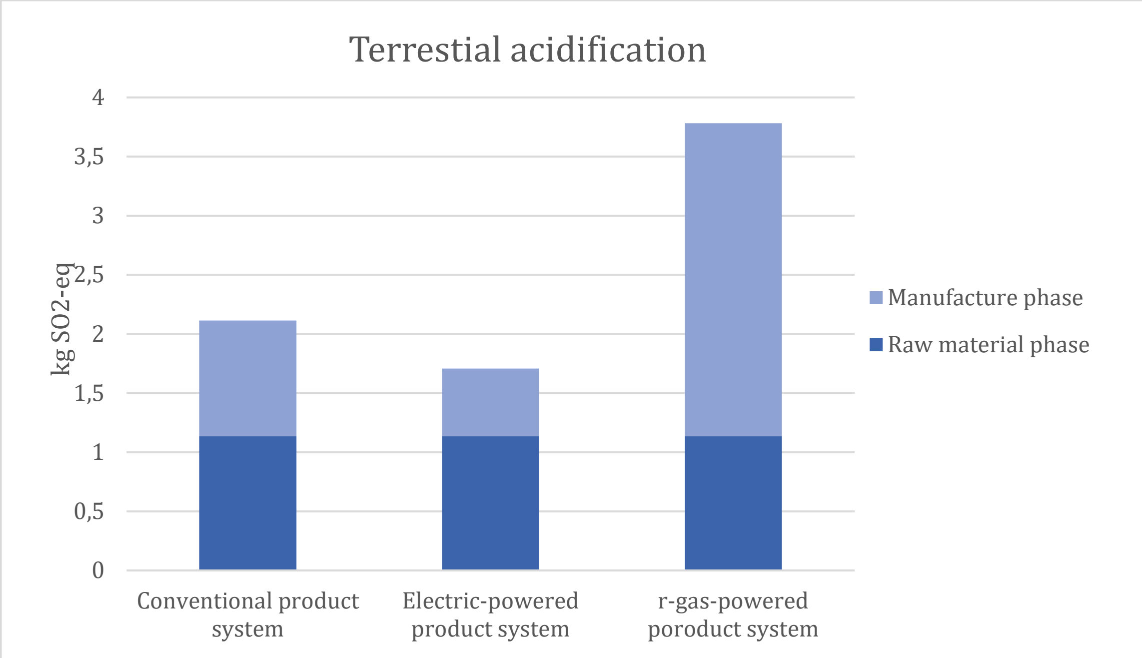
A11 Graphics of the impact categories



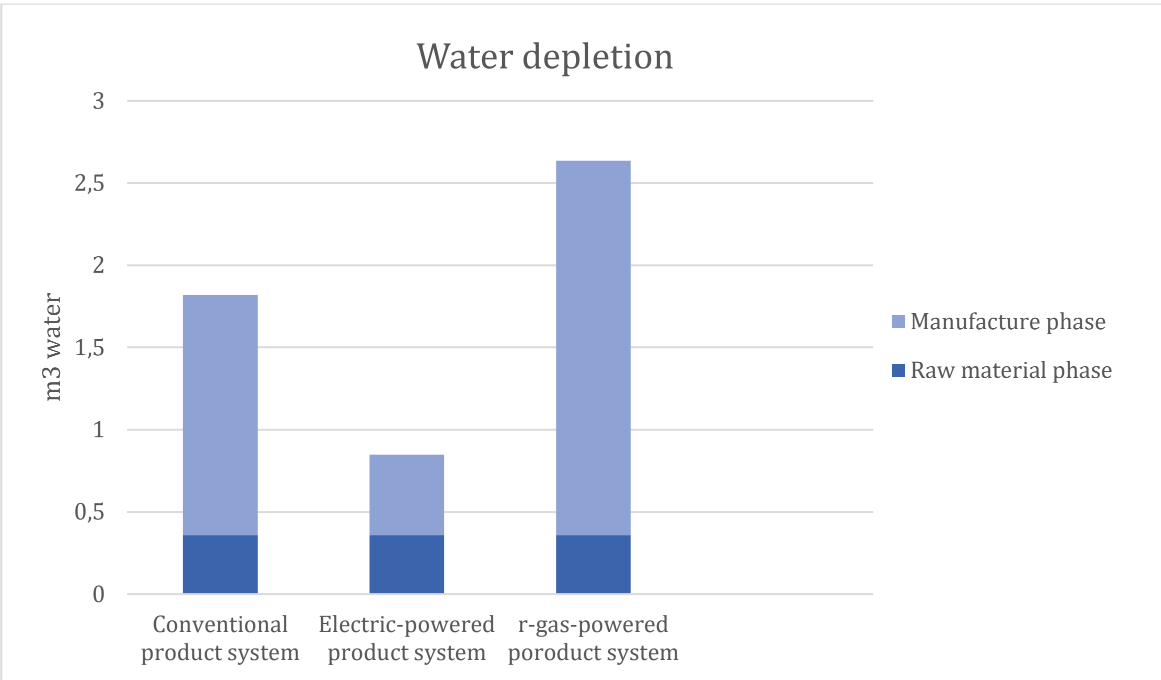
Graphic 8 Fossil depletion



Graphic 9 Ozone depletion



Graphic 10 Terrestrial acidification



Graphic 11 Water depletion

12 Sworn declaration

I assure you on oath that I did the above work on my own and I did not avail of someone else's help. All passages, which have been taken literally or by analogy from published or unpublished literature, have been identified correspondingly.

Date: 16.02.2018

Signature (Anna Grané Anglarill)