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Life Cycle Assessment of the Brayton Cycle in a Combined Cycle Hybrid Solar Central Receiver Power Plant

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Final year project presented in partial fulfilment of the requirements for the degree of Bachelor of Industrial Engineering at Stellenbosch University.

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Verklaring/Declaration

I, the undersigned, hereby declare that the work contained in this final year project is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Ek, die ondergetekende, verklaar hiermee dat die werk in hierdie finalejaarprojek vervat, my eie oorspronklike werk is en dat ek dit nog nie vantevore in die geheel of gedeeltelik by enige universiteit ter verkryging van ’n graad voorgelê het nie.

Sign on the dotted line:

………………………..	……………………..
	Datum
	Date

ECSA Exit level outcomes references

The following table includes references to sections in this report where ECSA exit level outcomes are addressed.

Exit level outcome	Section(s)	Relevant Application
1. Problem solving	Terms of reference, 1.1-1.2 5.2-5.3 6.1-6.3 Appendices A-G	Problem identified and formulated Methodology and calculations necessary to insert data into GaBi software Evaluate outcome/solution to problem Possible solution modeled and analyzed
2. Application of engineering & scientific knowledge	2.4 3.1-3.6 5.1-5.3 6.3	Basic calculations Thermodynamic calculations and chemistry applied Applying Life Cycle Assessment (LCA) technique in GaBi software Critically analyzing results
5. Engineering methods, skills & tools, incl. IT	4.1-4.6 5.2-5.3, Appendices A-G	Life Cycle Assessment method concerning environmental protection GaBi software – environmental sustainability tool
6. Professional & technical communication	This Report Throughout report, especially 3.1-3.6, 6.1, 6.3 and Appendix D.	The use of appropriate structure, style and language. The use of effective graphical support.
9. Independent learning ability	Throughout entire project	Literature study. Also, industrial engineering student figuring out very technical mechanical processes. Independently learning to use GaBi software.
10. Engineering professionalism	This Report	

Abstract

In the past decade global concern for energy security and the negative environmental impacts caused by fossil fuels has caused the global power industry to become more focused in a search for alternative energy sources and solutions. The need for renewable, sustainable green energy sources to reduce the long term impacts caused by current pollution is becoming evident and unavoidable. A promising solution proposes utilizing energy harnessed from the sun; it is clean, abundant and renewable (Bensebaa, 2010). There are different ways of introducing solar thermal energy into fossil fuel fired power generating plants currently in operation, presenting a partial or complete alternative to reduce or replace the usage of fossil fuels (Popov, 2011).

The Department of Mechanical and Mechatronic Engineering at Stellenbosch University is currently involved in the evaluation and development of different solar thermal power generating plants (Ficker, 2011). One of these plants, the model on which this project is based, is a hybrid combined cycle solar central receiver. This model utilizes a combined cycle referred to as the Stellenbosch University Solar Power Thermodynamic (SUNSPOT) cycle. This project addresses the Brayton cycle, the first cycle in the SUNSPOT combined cycle concept.

A Life Cycle Assessment (LCA) was chosen as the environmental sustainability technique to determine the impacts which the Brayton cycle will have on the environment. A Gate-to-Grave LCA has been conducted on the Brayton cycle, thus taking the operational life of the cycle as well as the disposal of its components into account. GaBi software has been used as environmental sustainability tool to conduct the LCA.

Interpreting the GaBi output showed that the global warming potential (GWP) is the indicator of the most significant environmental impacts of the Brayton cycle, thus the CO_2 emissions of the power plant are compared with several fossil fuelled power plants. It became clear that a hybrid solar combined cycle power plant has much lower carbon dioxide emissions than a conventional fossil fuel power plant. Notably, unlike solo solar thermal power plants, the carbon emissions are not small enough to be seen as negligible.

Opsomming

Wêreldwye belangstelling in alternatiewe energiebronne en –oplossings het die afgelope dekade dramaties toegeneem namate klimaatsverandering en energiesekerheid toenemend kommer gewek het. Dit het duidelik geword dat daar 'n wêreldwye behoefte bestaan om die kragnywerheid ten gunste van meer hernubare, volhoubare groen energiebronne te omvorm ten einde die langtermyn impak van die huidige besoedeling te verminder. Energie van die son is skoon, volop en hernubaar (Bensebaa, 2010). Om hierdie redes word dit beskou dat sonenergie 'n sleutelbydraer tot die energiebehoeftes van die toekoms gaan word (Bensebaa, 2010). Daar is verskillende maniere om sonhitte-energie in te bring in die fossielbrandstof gestookte kragopwekaanlegte wat tans in bedryf is, en dit bied 'n gedeeltelike of volledige alternatief om die gebruik van fossielbrandstowwe te verminder of vervang. (Popov, 2011)

Die Departement Meganiese en Megatroniese Ingenieurswese aan Stellenbosch Universiteit is tans betrokke by die evaluering en ontwikkeling van verskillende sontermiese kragopwekaanlegte (Ficker, 2011). Een van hierdie aanlegte, die model waarop hierdie projek gebaseer word, is 'n hibriede sentrale sonontvanger. Hierdie model benut 'n gekombineerde siklus bekend as die Stellenbosch University Solar Power Thermodynamic (SUNSPOT)-siklus. Hierdie projek behandel die Braytonsiklus, die eerste siklus in die SUNSPOT gekombineerdesiklus-konsep.

'n Lewensiklustaksering (LST) is gekies as tegniek vir omgewingsvolhoubaarheid om te bepaal watter impakte die Braytonsiklus op die omgewing sal hê. 'n Poort-tot-graf LST is op die Braytonsiklus uitgevoer en sodoende word sowel die bedryfslewe van die siklus as die beskikking van sy komponente in berekening gebring. GaBi-sagteware is gebruik as omgewingsvolhoubaarheids-instrument om die LST uit te voer.

Vertolking van die GaBi-uitset toon dat die GWP die aanwyser van die mees betekenisvolle omgewingsimpakte van die Braytonsiklus is, dus word die CO_2-vrystellings van die kragaanleg vergelyk met verskeie kragaanlegte wat op fossielbrandstof loop. Dit blyk duidelik dat 'n hibriede gekombineerdesiklus sonkragaanleg veel laer koolstofdioksiedvrystellings as 'n konvensionele fossielbrandstof-kragaanleg het. Dit is merkbaar dat die koolstofvrystellings, anders as by solo termiese sonkragaanlegte, nie klein genoeg is om as onbeduidend beskou te word nie.

Abbreviations

CSP - concentrating solar power
CRS - central receiver system
STP - solar thermal power
LCA - life cycle assessment
PV - photovoltaic
CO_2 - carbon dioxide
HRSG - heat recovery steam generator
GHG - greenhouse gas
J - joules
MJ - megajoules
kW - kilowatt
MW - megawatt
MWh - megawatt-hours
kg - kilograms and kilogramme
t - tonne
V - volume
P - pressure
atm - atmospheric pressure
T - temperature
K - Kelvin
s - seconds
c_p - specific heat capacity
D - diameter
r - radius
m - metre

Terms of reference

Problem statement

The Department of Mechanical and Mechatronic Engineering at Stellenbosch Universtiy is currently involved in the evaluation and development of a hybrid combined cycle solar central receiver power plant model. This model utilizes a combined cycle referred to as the Stellenbosch University Solar Power Thermodynamic (SUNSPOT) cycle. The project team has not determined the impact that this model will have on the environment.

Project objectives

This project addresses the Brayton cycle, the first cycle in the SUNSPOT combined cycle concept. The aim of the study is to determine the impact which this cycle will have on the environment during its operational life as well as the disposal phase. A Gate-to-Grave Life Cycle Assessment should be conducted on this cycle, using GaBi software as environmental sustainability tool.

Project limitations

- Data used and values calculated throughout this project to serve as input for the LCA in GaBi should firstly be validated and verified by a mechanical engineer before the final results of this study is used. This is because many estimations, assumptions and approximations were made concerning data about the SUNSPOT model, because data was not yet readily available.

- The Educational version of GaBi software was used for the purposes of this project. This version has some limitations, such as the incompleteness of its inventory database. This places a restriction on the accuracy and usability of the results.

- This project will be approached from an industrial engineering perspective, not mechanical engineering. Thus, despite limiting data, a well-developed framework to conduct a comprehensive and complete LCA of the Brayton cycle in the SUNSPOT model has been modelled and presented.

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Glossary

Insolation	Measure of solar radiation energy received on a given surface area in a given time. Commonly expressed as average irradiance in watts per square meter $(\frac{W}{m^2})$
Specific heat capacity (c_p)	The amount of heat, measured in joules, required raising the temperature of one kilogram of a substance by one Kelvin. Thus measured in $\frac{J}{kg.K}$
Isobaric process	Process in which pressure (P) remains constant
Adiabatic process	Thermally insulated process in which the net heat transfer to or from the working fluid is zero

1. Introduction

Global interest in alternative energy sources and solutions has increased dramatically in the past decade as climate change and energy security have caused rising concerns. In this chapter several reasons for the growing concern are introduced and solar technologies as solution are presented and discussed.

1.1 The need for alternative energy solutions

Fossil fuels such as oil, coal and natural gas are the primary sources of energy in the world today. In 2008 they already accounted for more than 80% of energy consumption globally (Greyvenstein, Correia and Kriel, 2008). It is predicted that the energy demand will grow by as much as 60% globally by the year 2030 (Greyvenstein, Correia and Kriel, 2008). In the process of harnessing the energy from these resources they are burned, emitting substances such as carbon dioxide (CO_2) into the air. Carbon dioxide is one of the greenhouse gases that contribute to global warming and burning coal also causes smog, acid rain and other air toxics.

Fossil fuels are non-renewable resources and are thus also not sustainable. It has become evident that there is a global need to transform the power industry to favouring more renewable, sustainable green energy sources to reduce the long term impact of current pollution. Serious immediate plans need to be made to limit the negative environmental impacts caused by fossil fuel powered plants, such as the greenhouse gas emissions (GHG) causing global climate change.

1.2 Solar energy as alternative energy solution

Energy from the sun is clean, abundant and renewable (Bensebaa, 2010). For these reasons solar energy is seen to become a key contributor to the energy demands of the future (Bensebaa, 2010). There are different ways of introducing solar thermal energy into fossil fuel fired power generating plants currently in operation, presenting a partial or complete alternative to reduce or replace the usage of fossil fuels. (Popov, 2011)

If solar power generation systems are continuously developed and improved on, incentives for investors and power utilities around the world will become increasingly attractive and solar power plants will have a significant contribution to global CO-emissions reduction (O'Keefe, 1997).

1.3 Solar technology options

There are two ways of harnessing energy from the sun: (1) Photovoltaic process (PV), using the light (photons) emitted by the sun, or (2) Solar thermal process, using the heat emitted by the sun. Solar thermal power (STP) plants produce approximately 80% of all solar based electricity generation, while only 20% is generated by PV systems (O'Keefe, 1997). O'Keefe (1997) explains solar photovoltaic as follows: "PV systems use PV cells that are semiconductor devices capable of converting photons from the sunlight *directly* into current."

By contrast, the solar thermal process includes concentrating solar power (CSP) which *indirectly* generates electricity using different physical technological setups to concentrate and harness the heat from the sun. This heat is used either to heat the heat transfer-fluid which heats water to produce water vapour to run the steam turbine, or to heat a working fluid (which may be a gas) to create combustion and the expansion of the working fluid then turns the gas turbine. Solar thermal technology variations include the following: (1) parabolic trough; (2) central receiver, (3) paraboloidal dish, (4) solar chimney and (5) the solar pond.

Generating electricity using a solar PV system is costly and very technical when applied to large commercial scale power plants, which makes its application impractical (Hu, et al., 2010). Solar PV is best utilized and is commonly in use in many residential and commercial buildings, with average installed power of about 3 kW and 50 kW, respectively (Bensebaa, 2010). Larger scale power outputs of at least 50 MW are generated by solar thermal methods, often with hybridization using natural gas (Bensebaa, 2010).

In a solar gas turbine this means that natural gas is used as ignition fuel in the combustion chamber in conjunction with the heated working fluid (such as compressed air) to assist in raising the temperature during combustion. The assistance of a fossil fuel component in solar power generation technologies ensures stability in electricity provision, given insolation fluctuations. It is possible to establish a solo solar thermal power station, although it is not that widely accepted and implemented because high costs and low efficiencies outweigh the benefits of such a plant. (Hu, et al., 2010) The power output instability caused by the insolation fluctuation causes solo solar thermal power systems to have lower and more fluctuating efficiencies than a hybrid system.

The model examined in this project is a central receiver solar thermal power technology, with natural gas hybridization and a combined cycle system.

1.4 Hybrid combined cycle Central Receiver System (CRS)

STP plants can reduce electricity costs when they are integrated into already-established fossil fuel fired power plants (Hischier, et al., 2009). Hybridisation refers to the addition of a fossil fuel for combustion in the Brayton cycle. Lower cost power generation is attributed to the constant and consistent energy despatchability that hybridization ensures (Hischier, et al., 2009). In this chapter the setup and operations of the hybridized central receiver technology are further discussed.

1.4.1 Physical setup of the central receiver

A central receiver, also referred to as a power tower or central tower, uses a tower to receive focused concentrated sunlight. It uses an array of large flat, movable mirrors (reflectors) called heliostats, that are arranged on the ground around the tower constantly repositioning itself to track the sun’s movement and focus its rays upon a central solar receiver mounted at the top of the tower (the focal point), as can be seen in

Figure 1 below. The focal point of the solar receiver tower is a key component, because it captures and transfers the solar thermal energy to the compressed working fluid (Hischier, et al., 2009).

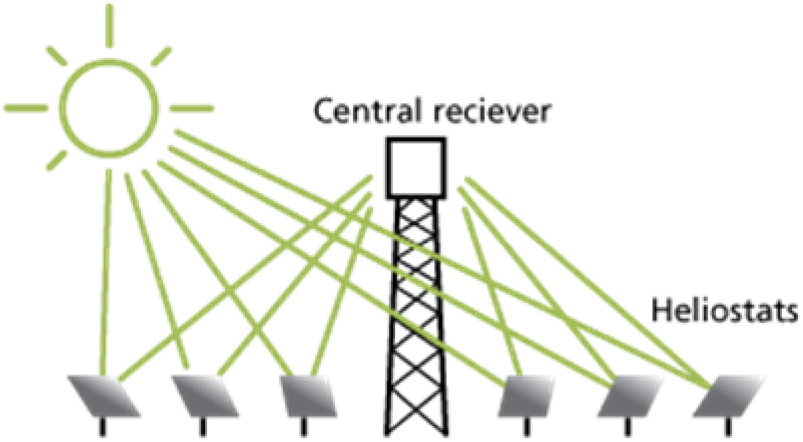

Figure 1 Basic heliostat configuration of a solar central receiver

Source: Solar thermal power production, 2000

1.4.2 Combined cycle system

The performance of a power generation system may be improved by integrating two thermodynamic cycles (Kakaras, Doukelis, Leithner and Aronis, 2004). The most common way of introducing and implementing cycle integration (called a combined cycle system) is adding a gas turbine to the existing steam powered plant to increase the plant's thermal efficiency and lifetime (Popov, 2011). This has become an attractive option because of the low fuel costs and overall high efficiency (Vant-Hull, 1998).

Combined cycle systems have much higher efficiencies because the exhaust heat from the one cycle is utilised as a heat source input to the second cycle instead of being waste heat. The output from the higher temperature cycle (Brayton) will be sufficient in providing a high enough heat source to the lower temperature cycle (Rankine) since heat engines can usually only utilise less than 50% of its energy created by fuel during combustion.

Figure 2 below depicts a representation of the processes within the system, showing how the output of the Brayton cycle is utilised to generate electricity directly and/or capture heat to serve as input to the Rankine cycle via the heat recovery steam generator (HRSG), also simply referred to as the steam generator. A Brayton gas turbine cycle has a compressor, a combustor and a turbine. The solar receiver is connected between the compressor and the combustion chamber (Vant-Hull, 1998). The input/operating temperature of such a gas turbine cycle is currently in a high range of approximately 900-1 350°C (Vant-Hull, 1998). The output is a gas at approximately 450-650°C. The Rankine cycle is the HRSG cycle used in steam engines and it requires an inlet temperature in the range of the Brayton cycle outlet temperature. This makes it possible to use otherwise wasted heat to drive a second cycle, improving overall efficiency. In fact, combined cycle efficiencies are already exceeding 60% (Kakaras, Doukelis, Leithner and Aronis, 2004).

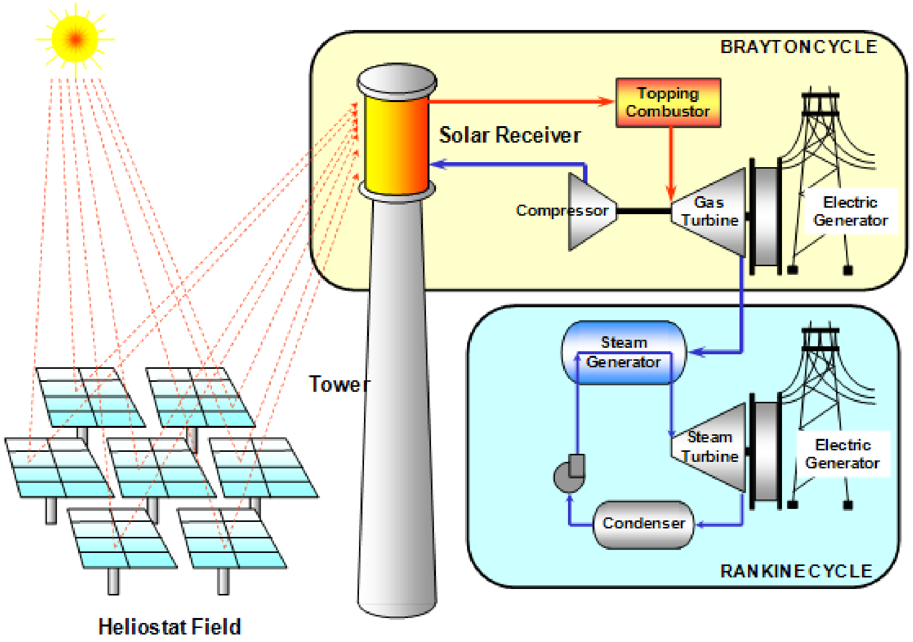

Figure 2 Scheme of a solar receiver system for electricity generation based on a Brayton-Rankine CC

Source: *ALSTOM – Solar-driven Combined Cycles*, n.d.

Central Receiver Systems (CRS) have the ability to work at much higher temperatures than any other STP technologies, which makes it possible to achieve higher electricity production efficiencies (Ortega, Burgaleta and Tellez, 2008). Thus it is feasible for solar energy to be the main high temperature heat source of combined cycles, because the benefits of the increased efficiency outweighs the costly initial capital investment needed for solar technologies (Vant-Hull, 1998).

1.4.3 Hybridisation

To ensure that the power generation output is stable, solar-fuel hybridization may be considered. This requires the burning of a fossil fuel in the combustion chamber of the Brayton cycle. The fuel is only used as a "helping hand" to ensure a constantly reliable stable supply of electricity when insolation levels fluctuate during operation (Vant-Hull, 1998). This is not clearly shown in Figure 2; natural gas should be shown as an input flow to the combustor in the Brayton cycle. All inputs, flows and processes will clearly be shown in detail in chapter 2 and chapter 3.

2. Stellenbosch University Solar Power Thermodynamic cycle (SUNSPOT) model

Having discussed the widely varying range of combinations available for the setup and implementation of solar central receiver systems, this section is devoted to discussing the setup and some specifications of the 100 MW model plant, possibly in the pipeline, that Stellenbosch Universtiy is involved in.

2.1 Background

The Department of Mechanical and Mechatronic Engineering at the University of Stellenbosch is currently involved in the evaluation and development of different solar thermal power generating plants (Ficker, 2011). One of these plants, the model that this project is based on, utilizes a combined cycle referred to as the SUNSPOT cycle. Prof Detlev Kröger proposed this cycle in 2008 as an appropriate and efficient cycle for generating electricity in South Africa.

This project addresses the Brayton cycle, the first cycle in the SUNSPOT combined cycle concept, by developing a Life Cycle Assessment (LCA) on it. To be able to do this as accurately as possible it is necessary to make certain estimations and assumptions about the plant model on which SUNSPOT is based. The Brayton cycle is fully discussed in chapter 3 and LCA in chapter 4. This model plant is now discussed in more detail.

2.2 SUNSPOT model operation

The SUNSPOT cycle is a combined cycle system, as discussed in section 1.4.2 above. This SUNSPOT cycle is shown below in Figure 3 below.

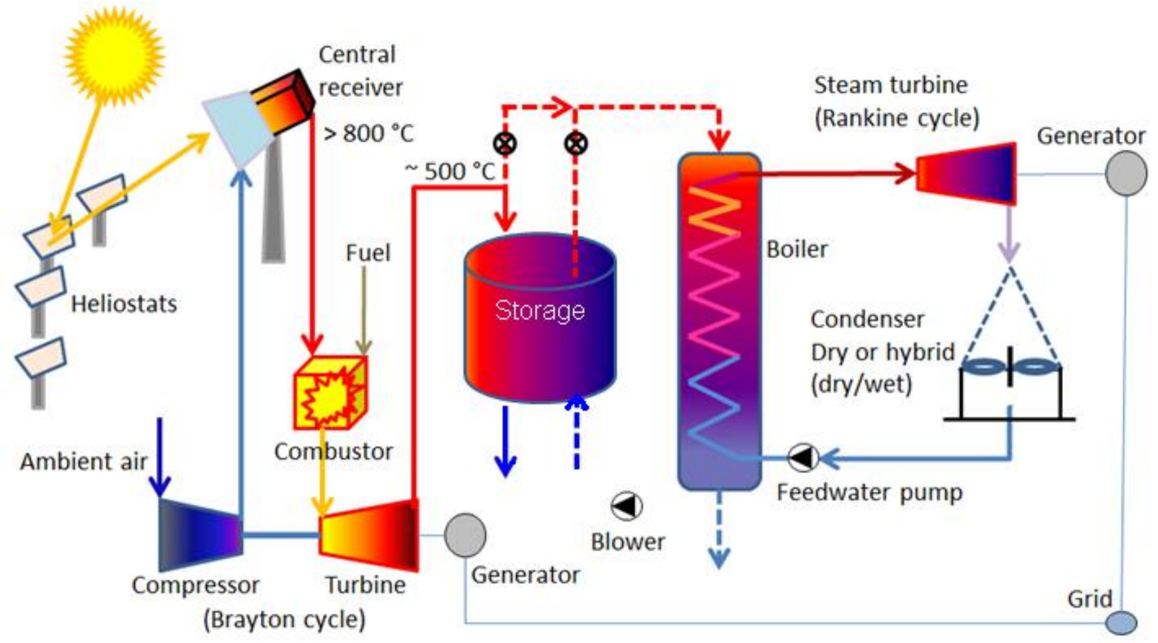

Figure 3 A schematic of the basic SUNSPOT cycle

Source: *Allen, K.G.,* 2011

In the SUNSPOT cycle compressed ambient air is heated to at least 800℃ in the central receiver. The hot air then flows through a turbine which drives the compressor and a generator that supplies electricity to a grid or transmission system (Harper, 2009). This is referred to as the Brayton cycle, which is discussed in detail in Chapter 3.

Air leaves the gas turbine at approximately 500℃ and flows into the concrete thermal storage facility. When the Brayton cycle is shut down after its daily 10 hour cycle, heated air from the storage facility is blown across a finned tube boiler. The boiler creates steam which moves through a steam turbine which drives a generator to supply electricity to the grid at night, referred to as the Rankine cycle. (Ficker, 2011)

It should be noted that the Brayton cycle and the Rankine cycle never operate simultaneously (Harper, 2009). The Brayton cycle runs during the day, generating electricity and charging the thermal store after which the cycle shuts down (Harper, 2009). This is why although the Brayton cycle only produces approximately $\frac{2}{3}$ of the total

100 MW electric power output by itself during the day, it is still referred to as a 100 MW range power plant, because it remains possible to run the Brayton cycle and Rankine cycle simultaneously and thus to produce 100 MW of electricity at any one specific time (Harper, 2010). For this project though, this concept of running the two cycles at the same time is not considered. We assume that the thermal storage tank is uniformly filled throughout the 10 hour cycle day. Harper (2009) makes it clear that the thermal store can either be in charge mode or discharge mode, it cannot do both simultaneously. It is thus important for the Brayton cycle to generate enough energy during the day to meet electricity demands, to drive the compressor and to ensure that the thermal store is sufficiently filled to keep the Rankine cycle running through the night.

The SUNSPOT cycle has natural gas hybridisation which stabilises the electrical power output of the gas turbine cycle. This is necessary due to fluctuations in solar radiation during cloudy or rainy periods lasting hours or even days.

2.3 Assumptions and model plant parameters

According to Harper (2009) this plant will have a solar receiver tower with a height of 100 m with 4000 heliostats surrounding it, each with an area of 100 m^2. It is assumed that this plant is able to work at peak capacity all around the clock if necessary, thus all values and calculations are based on peak values. The peak electric power output from the Brayton cycle is approximately $\frac{2}{3} * 100$ MW, although this value may be increased even more by adding more fuel to the combustion process. According to Harper (2009) the average plant efficiency during the whole year was 44%, assuming a plant life of 25 years.

The parameters for the 100 MW nominal plant are shown in Table 1 and Table 2 below.

Plant Specifications	***Value***
Tower height	100 m
Number heliostats	4 000
Heliostat area each	100 m^2

Peak thermal power onto receiver	278 MW
Combustion chamber exit temp	1 200 °C
Combustion chamber air flow (PEAK)	1 500 ton/hr
Combustion chamber air flow (not PEAK)	600 ton/hr
Compressor/Turbine pressure ratio (calculated)	14.80
Model plant electric capacity range	100 MW
Peak power electric (estimated $\frac{2}{3} * 100$)	66.67 MW
Peak turbine shaft power	158 MW
Average yearly system efficiency	44 %
Total cross section area pipes	20 m^2

Table 1 Solar field and gas turbine plant parameters for 100 MW plant

Source: *Report 3: Cost Modelling, April 2010*.

Specifications	***Value***
Mass thermal concrete	20 000 tons
Total cross section area pipes	20 m^2
Temp cold	300°C
Temp hot	500°C

Table 2 Thermal storage parameters for 100 MW plant

Source: *Report 3: Cost Modelling, April 2010*.

The content of this project will further on only focus on the Brayton cycle, the first part of the SUNSPOT cycle.

2.4 Pipe specifications

2.4.1 Pipe lengths, diameters and thickness

Assuming that the compressor and turbine are placed immediately at the base of the central receiver tower, which is 100 m high. This would require 100 m + 100 m = 200 m piping from the compressor to the receiver and back to the turbine via a combustor. The pipe length between the combustion chamber and the turbine is estimated to be 1 metre, which is short enough to minimise heat loss but long enough to allow for maintenance and movement between the turbine and combustor (Allen, 2011). For the same reasons the pipe length between the turbine outlet and the thermal storage facility is 3 meters. The thickness of the pipes is estimated to be 10 mm (Allen, 2011).

The cross sectional area of the pipes is given in table 1 as 20 m^2.

Thus $\pi r^2 = 20$ ....(2.1)

⇨ Radius (r) = $\sqrt[2]{\frac{20}{\pi}}$ = 2.523 m

⇨ Diameter (D) = 5.046 m ≅ 5 m

2.4.2 Pipe materials

The material used to manufacture the pipes between the compressor, receiver, combustor and turbine must be able to withstand high temperatures and pressures and still accommodate the flow. For the purpose of this project Inconel 600, a Nickel-based superalloy, is chosen for the composition of these pipes. A superalloy, also referred to as a high-performance alloy, is creep resistant at high temperatures, it is corrosion and oxidation resistant and its mechanical strength and fatigue resistance is excellent at high temperatures (DeGarmo, Black and Kohser, 1997). This is ideal for gas turbines and pipes with high temperature flows (DeGarmo, Black and Kohser, 1997). Inconel 600 has a melting point well over 1 425℃; it's composed of 72% Nickel (Ni), 17% Chromium (Cr) and 11% Iron (Fe). Its density is given as 8 400 $\frac{\mathrm{kg}}{\mathrm{m}^3}$ (China Special Alloy – CSA, 2010).

The pipe between the turbine outlet and the thermal storage facility does not need a superalloy to accommodate a temperature of 500℃. It is assumed that cast iron is used, which is sufficient to accommodate the temperature and pressure (DeGarmo, Black and Kohser, 1997). The density of cast iron is 7 800 $\frac{kg}{m^3}$ (The Engineering Toolbox, 2011).

2.4.3 Mass calculations of pipes

The parameters and estimations made in section 2.4.1 and section 2.4.2 are summarised below in table 3. These characteristics are used in this sub-section to calculate the mass of each pipe.

Description: Pipe region	*Length (m)*	*Diameter (m)*	*Thickness (m)*	*Materials*	*Density (kg/m^3)*
Compressor to receiver	100	5	0.01	Inconel 600: Super Alloy	8 400
Receiver to combustion chamber	100	5	0.01	Inconel 600: Super Alloy	8 400
Combustion chamber to turbine	1	5	0.01	Inconel 600: Super Alloy	8 400
Turbine to thermal storage facility	3	5	0.01	Cast iron	7 800

Table 3 Summarised values of model plant pipe specifications

2.4.3.1 Compressor to receiver / Receiver to combustion chamber:

Volume (V) = π * (outer radius^2 – inner radius^2) * length ....(2.2)

= π * [2.5^2 – (2.5 – 0.01)^2] * 100

= 15.677 m^3

8 400 $\frac{kg}{m^3}$ * 15.677 m^3 = 131 683 kg = 131.680 ton

2.4.3.2 Combustion chamber to turbine

From Equation(2.2)

V = π * [2.5^2 – (2.5 – 0.01)^2] * 1

= 156.765 * 10^{-3} m^3

8 400 $\frac{kg}{m^3}$ * 156.765 * 10^{-3} m^3 = 1 316.830 kg = 1.317 ton

2.4.3.3 Turbine to thermal storage facility

From Equation(2.2)

$$V = \pi * [2.5^2 – (2.5 – 0.01)^2] * 3$$

$$= 470.296 * 10^{-3} \text{ m}^3$$

$7\,800 \frac{kg}{m^3} * 470.296 * 10^{-3} \text{ m}^3 = 3\,668.312 \text{ kg} = 3.668 \text{ ton}$

3. Brayton Cycle

This chapter focuses only on the Brayton cycle, also referred to as the Joule Cycle, within the SUNSPOT model. The values of all input/output flows to and from the connecting processes within the Brayton cycle are determined in this chapter. To determine the influence every aspect of the cycle has on the environment, the above mentioned flows are necessary to be able to conduct the LCA described in chapter 4. This section is based on the specifications of the SUNSPOT model described in chapter 2.

The Brayton cycle is the fundamental thermodynamic underpinning of the gas turbine which is an internal continuous combustion engine. This cycle consists of three main components namely a compressor, a combustion chamber and a turbine. This can be seen in Figure 5 below, which is the specific schematic for the Brayton cycle in the SUNSPOT cycle model plant presented in this project. Next, in the following subsections, each process within this cycle is analysed separately.

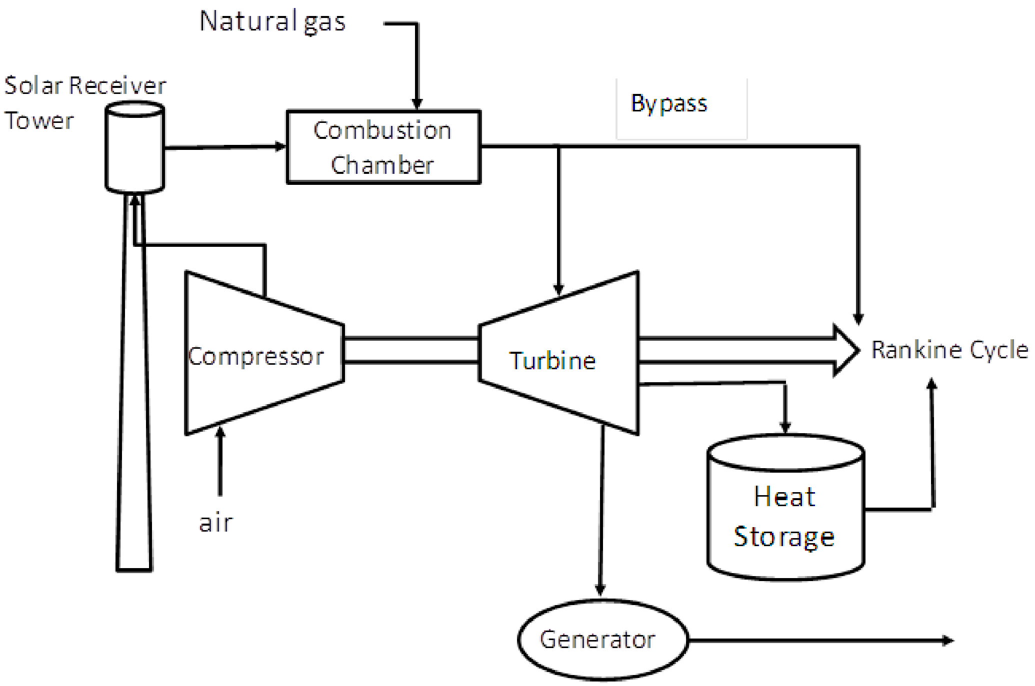

Figure 4 A schematic of the Brayton cycle within the SUNSPOT cycle system

3.1 Compressor

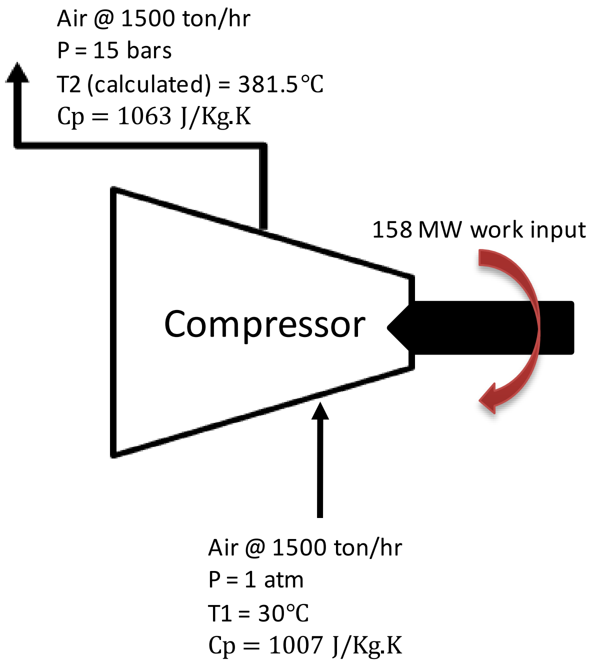

Figure 5 Brayton cycle compression process

Ambient air flows into the compressor at atmospheric pressure (P) (1.01325 bars). We assume the ambient temperature (T) at this pressure for a given location to be 30C. The mass flow of the air remains constant at 1 500 ton/hour while it is compressed to 15 bars by reducing its volume (V). During the compression of a gas the temperature is caused to increase, causing corrosion of the compressor blades. Cooling systems may be implemented to internally cool the blades of the compressor, minimising this unwanted effect. Entropy remains the same.

3.1.1 Calculation of outlet temperature

This process is referred to as an adiabatic process because no heat energy is added or taken away during the compression process. The theoretical temperature rise is calculated using the following formula:

$$T_2 = T_1 * Rc^{\frac{k-1}{k}} \qquad \ldots.(3.1)$$

T_2: unknown temperature after gas is pressurized (outlet temperature) in Kelvin (K)

T_1: known temperature before gas is pressurized (ambient inlet temperature) in Kelvin (K)

= 30 + 273.15 = 303.15 K

k = ratio of specific heats = approximately 1.4 for air

R_c = compression ratio = $\frac{15}{1.01325}$ = 14.80

From Equation(3.1)

Thus $T_2 = 303.15 * 14.80^{\frac{(1.4-1)}{1.4}} = 654.66$ K = 381.5℃

This heated compressed air leaves the compressor where it is heated even more by the solar tower (discussed in 3.2) before it progresses to the combustion chamber, discussed in 3.3.

3.1.2 Power calculations

There is a 158 MW shaft power *input* from the gas turbine which drives the compressor, thus the energy transfer is dissipated in driving the compressor. To calculate the energy added to the air per second (MW) during the compression process, the average of the specific heat capacity (c_p) of air at the inlet and outlet temperatures is used.

c_p of air @ 30℃ = 1 007 $\frac{J}{kg.K}$

c_p of air @ 381.5℃ = 1 063 $\frac{J}{kg.K}$

Thus the average is: $\frac{1\,007+1\,063}{2}$ = 1 035 $\frac{J}{kg.K}$

Energy added to the air per second (MW) because of the rise in temperature during compression is calculated as follows:

$$P = m * C_p * (T_f - T_i) \qquad \text{....(3.2)}$$

P = amount of heat energy gained or lost by substance per second $\frac{J}{sec}$ or (Watt)

m = mass flow of sample $\frac{kg}{s}$

C_p = heat capacity $\frac{J}{kg.K}$

T_f = final temperature (℃)

T_i = initial temperature (℃)

From Equation(3.2)

$$P = (1\,500\,000\,\frac{kg}{hr} \text{ x } \frac{1}{3600}\,\frac{hr}{sec}) \text{ x } 1\,035\,\frac{J}{kg.K} \text{ x } (381.5 - 30)\text{ K}$$

$$= 151.\,58\,\frac{MJ}{sec} = 151.58\text{ MW}$$

3.1.3 Calculation of compressor efficiency

Efficiency of the compressor is calculated as follows:

$$\frac{power\ output}{power\ input} * 100\% \qquad .\dots(3.3)$$

$$= \frac{151.58\,MW}{158\,MW} * 100\%$$

= 95.94% efficient

Thus the power (the energy that goes to waste per second) during compression equals:

158 – 151.58 = 6.42 MW

3.1.4 Energy calculations

- Energy air possesses at inlet flow

The volume of air that moves past the inlet is equal to 416.667 $\frac{kg}{s}$. This volume of air has energy equal to:

416.667 $\frac{kg}{s}$ * 1 007 $\frac{J}{kg.K}$ * (273.15 + 30) K * 1 second = 127 196 789.3 J = 127.20 MJ

- Energy air possesses at outlet flow

  The volume of air that moves past the outlet is equal to 416.667 $\frac{kg}{s}$. This volume of air has energy equal to:

416.667 $\frac{kg}{s}$ * 1 063 $\frac{J}{kg.K}$ * (273.15 + 381.5) K * 1 second = 289 955 627.8 J = 289.96 MJ

3.1.5 Physical specifications

Weight ≈ 150 ton (approximation made by linear upscale from *Solar Turbines incorporated*, 2011)

Material: Nickel-base superalloy (DeGarmo, Black and Kohser, 1997)

3.2 Solar receiver

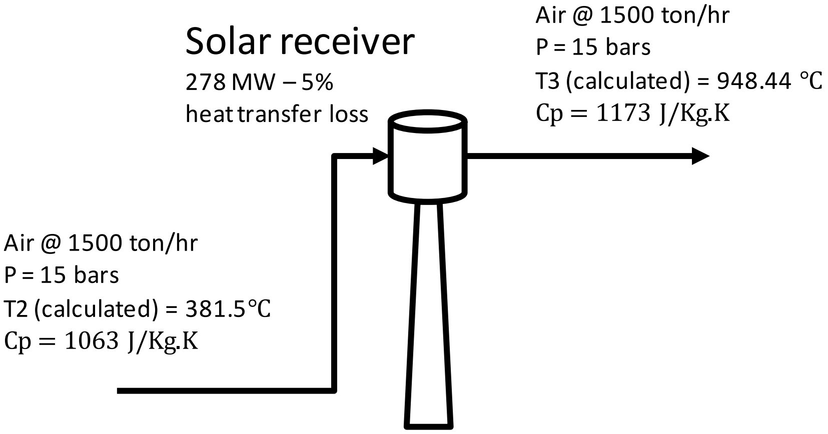

Figure 6 Solar receiver tower

The solar tower is used to heat the air to at least 800°C (Harper, 2009). The volume of the working fluid remain constant during this process.

3.2.1 Power calculations

Peak thermal power onto receiver according to Harper (2009) is *theoretically* 278 MW. This means that the focal point of the receiver is able to transfer 278 x 10^6 joules of heat energy per second to the air. To calculate the *actual* thermal energy transferred to the air we assume a 5% heat energy loss during the heat transfer process, therefore the *actual* peak thermal power onto receiver is:

$$278 * 0.95 = 264.1 \text{ MW}$$

Thus the energy loss per second (waste heat) is equal to 278 – 264.1 = 13.9 MW

3.2.2 Calculation of outlet temperature

Air approaches the receiver at 381.5°C. By iterating the equation below with the c_p values of air at 800°C, 900°C and 1 000°C separately, it is found that the outlet temperature will be the closest to 900°C , so the c_p value of air at the outlet temperature is assumed to be approximately the same as the c_p value for air at 900°C.

Using this the average c_p value for air during this heating process is calculated:

c_p of air @ 381.5°C $= 1\ 063 \frac{J}{kg.K}$

c_p of air @ 900 °C $= 1\ 173 \frac{J}{kg.K}$

Thus the average is: $\frac{1\ 063+1\ 173}{2} = 1\ 118 \frac{J}{kg.K}$

Theoretic calculation of the solar receiver outlet temperature x, given that the average specific heat capacity (c_p) is used:

From Equation(3.2)

$$(1\ 500\ 000 \frac{kg}{hr} * \frac{1}{3600} \frac{hr}{sec}) * 1\ 118 \frac{J}{kg.K} * (x - 381.5) \text{ K} = 264.1 \text{ MW}$$

$$\text{Thus } x = 948.44°\text{C}$$

3.2.3 Energy calculations

- Energy air possesses at inlet flow

  This is equivalent to the energy the air possesses at the outlet flow of the compressor, as calculated in section 3.1.4.

⇨ 289.96 MJ each second

- Energy air possesses at outlet flow

  The volume of air that moves past the outlet is equal to 416.667 $\frac{kg}{s}$. This volume of air has energy equal to:

$$416.667\ \frac{kg}{s}\ *\ 1173\ \frac{J}{kg.K} * (273.15 + 948.44)\ \mathrm{K} * 1\ \mathrm{second} = 597\ 052\ 590.1\ \mathrm{J}$$
$$= 597.05\ \mathrm{MJ}$$

3.3 Combustion chamber

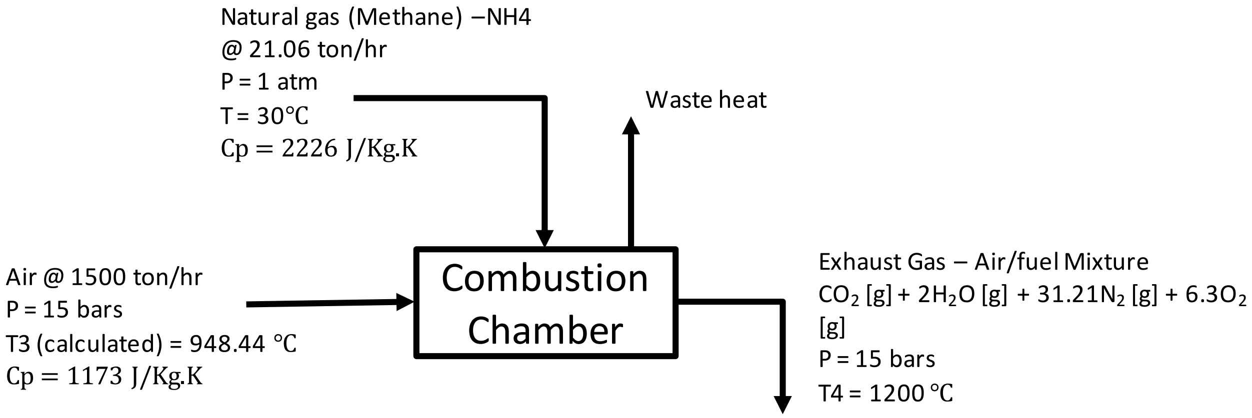

Figure 7 Brayton cycle combustion process

The highly heated pressurized air, at this point 948.44℃ and 15 bars, enters the combustion chamber at a constant 1 500 tons/hr. It is in this stage that the natural gas is added to the process for hybridization. Harper (2010) states that the mass flow of the natural gas is 21.06 tons/hr. As previously discussed, the fuel aids in raising the temperature of the air even more during burning ("combustion"). The fuel and air mix and are then ignited. This is an isobaric process, which means combustion takes place at a constant pressure, while the temperature, volume and entropy increase. Even though there is waste heat that escapes this process, the temperature increases sufficiently to ensure an outlet temperature of 1 200°C (Harper, 2009).

3.3.1 Chemical combustion reaction

Methane (CH_4) is the principal component of natural gas. For combustion only the combustion of CH_4 in air is assumed. Air consists mainly of oxygen (O_2) and nitrogen (N_2). There is more air entering the chamber than will react with the methane during combustion. *Theoretical* air is the minimum amount of air needed for complete combustion. In this section the *actual* combustion equation is determined, which takes the excess air into account and shows the chamber's exhaust gas mixture.

The theoretical *stoichiometric* combustion of methane in air, before excess air is determined, is represented by the following chemical reaction:

$$CH_4\,[g] + 2(O_2\,[g] + 3.76\ N_2\,[g]) \rightarrow CO_2\,[g] + 2H_2O\,[g] + 7.52\ N_2\,[g]$$

The elements present during combustion, their symbols and atomic weights may be found in the Periodic Table which is attached as Appendix A. Table 4 below summarises extracts of the applicable elements and their values for combustion.

Element	***Symbol***	***Molecular mass*** $\frac{g}{mol}$
Carbon	C	12.011 = ~ 12
Oxygen	O	15.999 = ~ 16
Nitrogen	N	14.007 = ~ 14
Hydrogen	H	1.008 = ~ 1

Table 4 Summary of atomic masses of elements used in the combustion of natural gas in air

Theoretical air-fuel ratio (A/F) on mass base is determined; using Table 4 above, the calculation follows:

$$(\text{A/F})_{\text{mass}} = \frac{2*\ 16*2+3.76*2*14}{12*(1*4)} = \frac{274.56}{16} = 17.16$$

The mass flow into the combustion chamber is 21.06 tons/hr natural gas and 1 500 tons/hr air. Thus the actual air-fuel mass ratio is:

$$\frac{1500\,\frac{ton}{hr}}{21.06\,\frac{ton}{hr}} = 71.225 \text{ dimensionless}$$

Actual air-fuel ratio (A/F) on mass base is determined as follows:

$$(\text{A/F})\text{ mass } = \frac{actual\ air - fuel\ mass\ ratio}{theoretical\ \ air - fuel\ mass\ ratio} \qquad \ldots.(3.4)$$

$$= \frac{71.225}{17.16} = 4.151$$

This means that there are 415.06% *theoretical air* and 315.06% *excess air* in the combustion chamber system. The *actual* combustion equation becomes as follows:

$$CH_4\,[g] + 4.15*2(O_2\,[g] + 3.76\ N_2\,[g]) \rightarrow CO_2\,[g] + 2H_2O\ [g] + 4.15*7.52\ N_2\,[g] + 6.3O_2\,[g]$$

$$CH_4\,[g] + 8.3O_2\,[g] + 31.21N_2\,[g]) \rightarrow CO_2\,[g] + 2H_2O\ [g] + 31.21N_2\,[g] + 6.3O_2\,[g]$$

The left side (reactants) of the equation comprises the inputs to the chamber and the right side (products) comprises the output of the chamber, the composition of the air-fuel mixture exhaust gases.

3.3.2 Mass calculations

For all following calculations a *time period of 1 second* is assumed.

3.3.2.1 Reactants

- Methane (NH_4): 21 056.75 $\frac{kg}{hr}$ * $\frac{1}{3600}\frac{hr}{sec}$ = 5.849 $\frac{kg}{sec}$

  Thus because a 1 second time period is assumed, it may be said that there are 5.849 kg of CH_4 to react.

- Air (O_2 + 3.76 N_2) :

  1500 000 $\frac{kg}{hr}$ * $\frac{1}{3600}\frac{hr}{sec}$ = 416.667 $\frac{kg}{sec}$
  Thus because a 1 second time period is assumed, it may be said that there are 416.667 kg of air to react.

  X * (O_2 + 3.76 N_2) = 416.667 kg
  X * (32 + 3.76*28) = 416 666.67 g
  X = 3035.16 mol

  Thus there are 3035.16 mol * 32 $\frac{g}{mol}$ = 97 125.10 g
  ⇨ 97.125 kg O_2

  Thus there are 3035.16 mol * 3.76*28 $\frac{g}{mol}$ = 319 541.65 g
  ⇨ 319.542 kg N_2

3.3.2.2 Products

The sum of the separate product masses equals the sum of the reactants masses. Thus the mass of the products for *one second* together must be:

$$(1500\,000 + 21\,056.75)\,\frac{kg}{hr} * 1\,000\,\frac{g}{kg} * \frac{1}{3600}\,\frac{hr}{sec} = 422\,515.764\,\frac{g}{sec}$$

Thus because a 1 second time period is assumed, it may be said there are 422.515 kg of products.

$X * (CO_2 + 2H_2O + 31.21\ N_2 + 6.3O_2) = 422\ 515.764$ g

$X * (44 + 2*18 + 31.21*28 + 6.3*32) = 422\ 515.764$ g

⇨ $X = 365.663$ mol

Product Masses:

- For CO_2: $44\,\frac{g}{mol} * 365.663$ mol = 16089.04 g = 16.09 kg
- For H_20: $(2*18)\,\frac{g}{mol} * 365.663$ mol = 13 163.76 g = 13.16 kg
- For N_2: $(31.21*28)\,\frac{g}{mol} * 365.663$ mol = 319 542.96 g = 319.54 kg
- For O_2: $(6.3*32)\,\frac{g}{mol} * 365.663$ mol = 73 717.056 g = 73.72 kg

3.3.2.3 Mass flow

The combustion chamber and the turbine are closed systems, meaning that no exchange of matter (mass) takes place with the systems surroundings, only heat may be exchanged. Thus the outlet mass flow of the combustion chamber is the inlet mass flow to the turbine, and the mass flow of the exhaust gas leaving the combustion chamber (the products) is equal to the sum of the separate mass flows entering the chamber (reactants):

$$5.849\,\frac{kg}{sec} + 416.667\,\frac{kg}{sec} = 422.52\,\frac{kg}{sec}$$

3.3.3 Energy calculations

All the necessary information is known for calculating the energy transferred during combustion. The specific heat capacity (c_p) values of the reactants and products at their current temperatures are shown in Table 5 below. These values, together with the mass of each reactant and product calculated in 3.3.2, are used to determine the energy contribution made by each substance during combustion.

Substance (gaseous form)	*Symbol*	*Temp℃*	*Specific heat capacity (c_p) $\frac{J}{kg.K}$*
Methane	CH_4	30	2 226
Oxygen	O_2	1 200	1 143
Nitrogen	N_2	1 200	1 244
Carbon dioxide	CO_2	1 200	1 326
Water vapour	H_2O	1 200	2 609

Table 5 Specific heat capacities of reactants and products of combustion

3.3.3.1 *Reactants*

There are two sources of energy flows into this process, the first is the energy which natural gas (methane) possesses at the inlet, calculated as follows:

Methane (CH_4):

$$2226 \frac{J}{kg.K} * 5.849 \text{ kg} * 303.15 \text{ K} = 3\,946\,974.80 \text{ J} = 3.95 \text{ MJ}$$

The second source of energy inflow is the heated air flowing from the receiver to the combustion chamber inlet, the energy this air possesses has been calculated in section 3.2.3 to be 597.05 MJ.

Sum of Reactant Energies: 601 MJ each second

3.3.3.2 Products

- CO_2 : 1326 $\frac{J}{kg.K}$ * 16.09 kg * 1473.15 K = 31.43 MJ
- H_2O: 2609 $\frac{J}{kg.K}$ *13.16 kg * 1473.15 K = 50.58 MJ
- N_2 : 1244 $\frac{J}{kg.K}$ * 319.54 kg * 1473.15 K = 585.89 MJ
- O_2 : 1143 $\frac{J}{kg.K}$ * 73.72 kg * 1473.15 K = 124.13 MJ

Sum of Product Energies = 792.03 MJ each second

Thus the energy added per second to the system (power generated) through the combustion of natural gas in air is 792.03 MW – 606.22 MW = 185.81 MW

3.3.4 Physical specifications

Weight ≈ 5 tons (van Schalkwyk, 2011)

Material: Nickel-base superalloy (DeGarmo, Black and Kohser, 1997)

3.4 Gas turbine

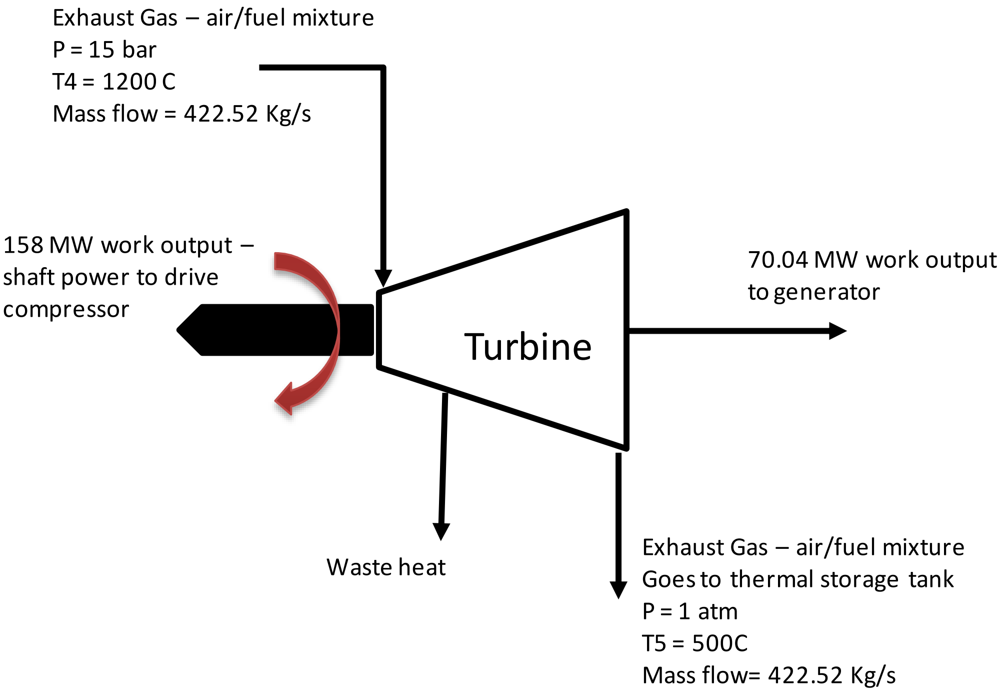

Figure 8 Brayton cycle gas turbine process

Gas turbines used in combined cycles have much higher efficiencies than turbines used in single cycles. This is because although there is still some heat wasted during this process, most of the waste heat is recovered and used by a heat recovery steam generator (HRSG). Single cycle gas turbines have efficiencies ranging between 25-30% and may sometimes be up to a maximum of 40%. The analysis of the turbine for the purpose of this project is based on the Siemens Gas Turbine (SGT6)-8000H, which is characterized by high efficiency and low life-cycle costs (Siemens Energy, 2011). It has very high efficiency levels, being most economical for power generation in combined-cycle systems (Siemens Energy, 2011). It has a power output of 274 MW, being sufficient to generate the desired 228.04 MW and leaving room for the upscale of the power plant for generating more power by the addition of more fuel for combustion. It has a single cycle efficiency of up to 40% and a combined cycle turbine thermal outlet efficiency of >60%. It accommodates pressure ratios of up to 20 and exhaust mass flows of up to 600 kg/s. This is all consistent with the SUNSPOT model.

The highly heated (1 200℃) and compressed (15 bars) air-fuel exhaust gas mixture from the combustion chamber enters the turbine expanding. It passes through the turbine which turns a shaft connected to the rotor of a generator, which then also turns within the stator of the generator. This process generates electricity. The turbine supplies 70.04 MW as input power to the generator, as seen in section 3.5. At the same time the rotating shaft generates 158 MW which drives the compressor (Harper, 2010). This is illustrated in Figure 10 above.

3.4.1 Power calculations

3.4.1.1 C_p-value calculation

Exhaust Gas – air/fuel mixture composition: $CO_2 + 2H_2O + 31.21N_2 + 6.3O_2$

Substance (in gaseous form)	*Symbol*	*Temp* ℃	*Specific heat capacity (c_p)* $\frac{J}{kg.K}$
Oxygen	O_2	500	1 043
Oxygen	O_2	1 200	1 143
Nitrogen	N_2	500	1 110
Nitrogen	N_2	1 200	1 244
Carbon Dioxide	CO_2	1 200	1 326
Carbon Dioxide	CO_2	500	1 148
Water vapour	H_2O	1 200	2 609
Water vapour	H_2O	500	2 113

Table 6 Specific heat capacities of air/fuel mixture at the inlet and outlet temperatures of the turbine

Weighted average of c_p-values at inlet temp of 1200℃:

$$\left(\frac{1}{40.51}\right)*1326 + \left(\frac{2}{40.51}\right)*2609 + \left(\frac{31.21}{40.51}\right)*1244 + \left(\frac{6.3}{40.51}\right)*1143 = 1\ 297.71\ \frac{J}{kg.K}$$

Weighted average of c_p-values at outlet temp of 500℃:

$$(\frac{1}{40.51})*1\ 148 + (\frac{2}{40.51})*\ 2\ 113 + (\frac{31.21}{40.51})*1\ 110 + (\frac{6.3}{40.51})*1\ 043 = 1\ 150.04\ \frac{J}{kg.K}$$

Average C_p –value of exhaust gas used in the heat transfer process of the gas turbine:

$$\frac{1\ 297.71 + 1\ 150.04}{2} = 1\ 223.87\ \frac{J}{kg.K}$$

3.4.1.2 *Power generated (input power)*

Power is generated in the gas turbine system by the temperature drop (heat energy transfer) by the expansion of the exhaust gas through the turbine, as previously discussed. Some heat is dissipated through the system, referred to as waste heat. The power is calculated as follows:

From Equation (3.2)

$$P = 422.515\ \frac{kg}{s}\ \ \text{x}\ 1\ 223.87\ \frac{J}{kg.K}\ \ \text{x}\ (1\ 200\text{-}500)\ \text{K}$$

$$= 361.97\ \frac{MJ}{sec} = 361.97\ \text{MW}$$

This power is used as work output to drive the shaft driving the compressor and to drive the rotor driving the generator.

3.4.1.3 *Net power output*

The SGT6-8000H has efficiency's >60% for combined-cycle systems (Siemens Energy, 2011). For our specific model an efficiency of 63% is assumed. The net power output, which is the useful power that will *actually* be used to drive the compressor and the generator, is calculated as follows:

361.97 MW *63% = 228.04 MW

Thus the wasted power (energy per second) during this process is equal to 361.97 – 228.04 = 133.96 MW

The output shaft power that drives the compressor is given as 158 MW (table 1, section 2.3), thus the output power that drives the generator is 228.04 – 158 = 70.04 MW

3.4.2 Energy calculations

- Energy exhaust gas possesses at inlet flow:

  This is equivalent to the energy the exhaust gas possesses at the outlet flow of the combustion chamber.

  => 792.03 MJ

- Energy exhaust gas possesses at outlet flow:

  To calculate the total energy the exhaust gas possesses at the turbine outlet, one first determines each substance's separate energy contribution and then sums them together. The same calculation method is used as previously done in section 3.3.3.2. Using c_p values at a temperature of 500℃ from table 6 (section 3.5.1.1) it follows:

  - CO_2 : 1 148 $\frac{J}{kg.K}$ * 16.09 kg * 773.15 K = 14 281 101.06 J = 14.28 MJ
  - H_2O: 2 113 $\frac{J}{kg.K}$ *13.16 kg * 773.15 K = 21 499 043.9 J = 21.50 MJ
  - N_2 : 1 110 $\frac{J}{kg.K}$ * 319.54 kg * 773.15 K = 274 228 109.6 J = 274.23 MJ
  - O_2 : 1 043 $\frac{J}{kg.K}$ * 73.72 kg * 773.15 K = 59 447 472.57 J = 59.45 MJ

  Sum of exhaust gas energies = 369.46 MJ

3.4.3 Physical specifications

Weight = 280 tons (Siemens Energy, 2011)

Material: Nickel-base superalloy (DeGarmo, Black and Kohser, 1997)

3.5 Generator

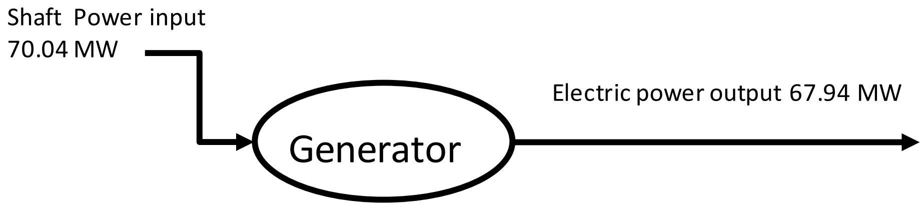

Figure 9 Power flow in generator process of Brayton cycle

3.5.1 Power calculations

The gas turbine provides 70.04 MW shaft power (as calculated in section 3.4.1.3) to the generator to drive its rotor. Generator efficiency is assumed to be 97%. Thus, as shown in Fig 9 above, the peak electric power generated by the Brayton cycle generator is:

$$70.04\ \text{MW} * 97\% = 67.94\ \text{MW}$$

Harper (2010) gives the Brayton cycle peak electric power output estimation as 66.67 MW; this can be seen in table 1 of section 2.3. Comparing Harper's value with the one calculated above it can be seen that they are approximately equivalent, thus validating the model.

3.5.2 Physical specifications

Weight ≈ 387 tons (approximation made by linear upscale from *Solar Turbines incorporated*, 2011)

Material: 35% Cast iron
40% Carbon steel
25% Copper wire
(Van Schalkwyk, 2011)

3.6 Thermal storage facility

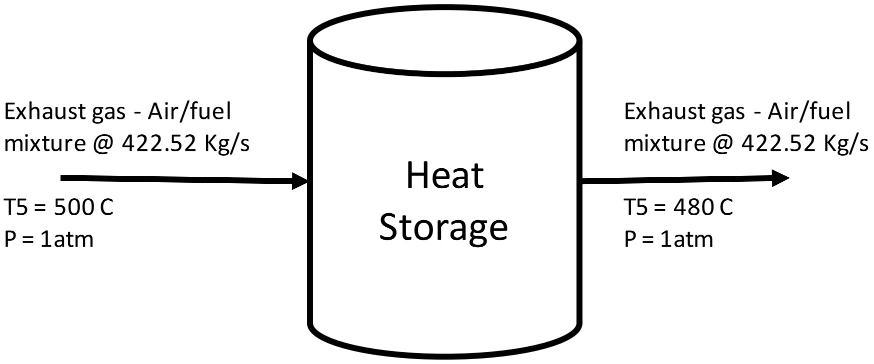

Figure 10 Process of storing heat in a thermal storage facility

The Brayton cycle runs for 10 hours during the day, while the Rankine cycle runs during the night (Harper, 2010). The thermal storage tank must capture enough heat energy during the day to be able to supply sufficient to the Rankine cycle during the night. The exhaust gas leaves the turbine decompressed to 1 atm at a temperature of approximately 500℃. The high temperature turbine exhaust gas continually flows into the thermal storage facility made of concrete at 422.52 kg/s, before being released into the air (Harper, 2010). This process is comprehensively depicted in figure 4, chapter 2.2.

3.6.1 Energy calculations

- Energy exhaust gas possesses at inlet flow:

  This is equivalent to the energy the exhaust gas possesses at the outlet flow of the gas turbine.

  => 369.46 MJ

- Energy exhaust gas possesses at outlet flow:

  To calculate the total energy the exhaust gas possesses at the outlet of the heat storage facility, we first determine each substance's separate energy contribution and then sum them. The same calculation method is used as previously done in section 3.3.3.2 and section 3.5.2, at a temperature of 480℃. It follows:

  - CO2 : $1\ 148\ \frac{J}{kg.K} * 16.09\ kg * 753.15\ K = 13\ 911\ 674.66\ J = 13.91\ MJ$

- H2O: 2 113 $\frac{J}{kg.K}$ *13.16 kg * 753.15 K = 20 942 902.3 J = 20.94 MJ
- N2 : 1 110 $\frac{J}{kg.K}$ * 319.54 kg * 753.15 K = 267 134 321.6 J = 267.13 MJ
- O2 : 1 043 $\frac{J}{kg.K}$ * 73.72 kg * 753.15 K = 57 909 673.37 J = 57.91 MJ

Sum of exhaust gas energies = 359.89 MJ

Thus the heat (energy) wasted during this process is equal to 359.89 – 369.46 = 9.57 MJ

3.6.2 Physical specifications

Weight = 20 000 tons (Harper, 2010)

Material: Concrete (Harper, 2010)

4. Life Cycle Assessment

This chapter introduces the concept of Life Cycle Assessment (LCA) as an environmental sustainability analysis and assessment technique.

4.1 Life Cycle Assessment methodological framework

As described in Chapter 1 (section 1.1) the global environmental concern has increased substantially in the past decade. The increased awareness and realisation of the importance of environmental impacts and the protection thereof have been supported globally. This has made room for the development of many methods and techniques to determine the extent of the impact that specific operations and processes have on the surrounding environment. LCA is such a technique.

LCA study presents the environmental aspects/factors and their potential impacts or consequences. This approach may be applied throughout a product system's entire life cycle from the raw material extraction and acquisition through the production of material, the usage thereof, the end-of-life treatment, recycling and final disposal (ISO 14040:2006(E)). This approach is referred to as cradle-to-grave analysis. There are other versions of an LCA in which the study is not conducted from raw material extraction, but rather from some point downstream; this approach may be referred to as gate-to-grave or gate-to-gate, depending on the end-point of the LCA study.

Other environmental management techniques include risk assessment, environmental performance evaluation, environmental auditing and environmental impact assessment (EIA). It is important to note that although life cycle assessment is a highly esteemed technique to use, it is not always the most appropriate technique to use in every given situation. There are factors that an LCA does not address that may be crucial to include in the decision-making process of a specific situation. Such factors, that lie beyond the scope of an LCA study, include economic or social aspects. (ISO 14040:2006(E))

The ISO 14040 series of LCA standards gives the principles and framework for conducting an LCA study. ISO 14044 details the requirements for the entire process duration of an LCA. ISO 14040 (2006(E)) states that, "LCA assesses, in a systematic way, the environmental aspects and impacts of product systems, from raw material acquisition to final disposal, in accordance with the stated goal and scope". There are four phases in an LCA study which are discussed further in detail in section 4.2-4.5; they are: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase and the interpretation phase. (ISO 14040:2006(E))

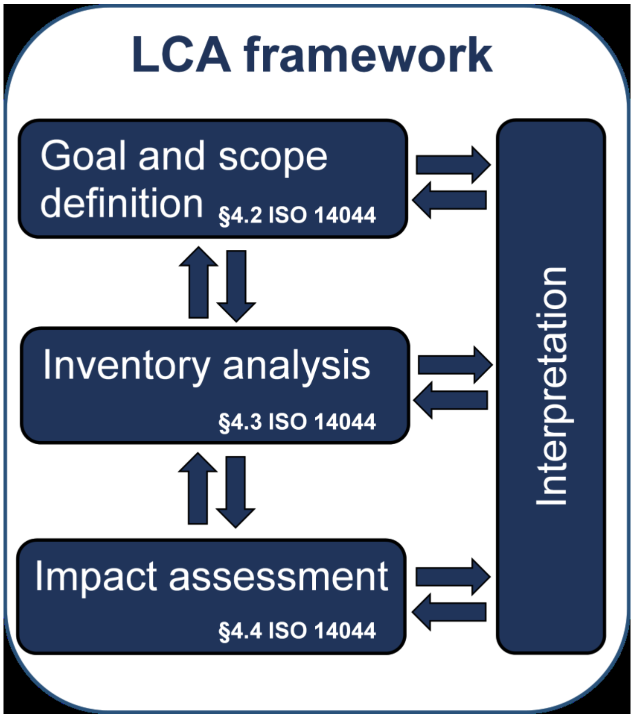

Figure 11 Life cycle assessment framework

Source: GaBi Software, 2009

4.2 Goal and scope definition

The ISO 14040 standard states that the first phase or step when conducting an LCA is to define the goal and scope. Both the goal and the scope of the study should be well defined initially, clearly and sufficiently to address the intended application. Because of the iterative nature of the LCA process it is necessary to modify or redefine the scope later on in the process after output of results to meet the original goals of the LCA study. (ISO 14040:2006(E)) (GaBi Software, 2009).

Within the goal definition of an LCA there are several points that need to be determined; these include intended application of study, purpose for conducting the study, the audience intending to present results to and the usage for comparative analysis (ISO 14040:2006(E)) (GaBi Software, 2009).

The process of defining the scope should include evaluation of the following sections, as stipulated in the ISO standards:

- Functions of product system
- Functional unit
- Reference flow
- Description of the system
- System boundaries
- Allocation procedures
- Impact categories selected and methodology of the impact assessment method
- Data requirements
- Data assumptions
- Limitations
- Initial data quality requirements
- Critical review
- Reporting type and format

(ISO 14040:2006(E)) (GaBi Software, 2009)

4.3 Inventory analysis

The iterative Life Cycle Inventory (LCI) analysis/assessment consists mainly of data collection and data calculation processes that involve the compiling and quantifying of all inputs and outputs of the system (ISO 14040:2006(E)) (GaBi Software, 2009). This is done for all the life cycle stages of the product system and is the most time consuming phase (GaBi Software, 2009). Because of the iterative nature of this process, it is important to keep measuring data requirements/limitations against the original goals and scope of the study to ensure that they are met (ISO 14040:2006(E)).

The Data Collection phase requires the greatest amount of time and work of all the phases in an LCA. The process consists of the collection of quantitative and qualitative data for each unit process within the system. All constraints/limitations on the process of data collection must be recorded in the scope definition. (GaBi Software, 2009)

More in-depth information on data collection and data calculation may be found in ISO 14044.

4.4 Impact analysis

In this phase of the Life Cycle Impact Assessment (LCIA) the potential environmental impacts that come from the LCI are identified, evaluated and their significance is assessed (ISO 14040:2006(E)) (GaBi Software, 2009). An approach is used to try to understand environmental impacts in which certain inputs and outputs (inventory data) from the LCI are related to very specific environmental impact categories by assigning each of these inputs and outputs to a specific category (ISO 14040:2006(E)).

Certain elements of the LCIA are defined in the scope definition of the LCA study (GaBi Software, 2009). Some elements that cannot be excluded from the scope include the identification of relevant impact categories, classification and characterization (GaBi Software, 2009). To assist in the process of ensuring that the study's goals are met, the goal and scope of the LCA may be iteratively reviewed within the impact analysis phase (ISO 14040:2006(E)). If the results indicate that the goals are unachievable, the goals may be modified or redefined accordingly (ISO 14040:2006(E)).

The LCIA involves many steps, stipulated in the ISO standard and defined in detail in the ISO 14044 standard. The output of the LCIA phase provides information input to the life cycle interpretation phase, discussed in the next section (ISO 14040:2006(E)).

4.5 Interpretation phase

In the interpretation phase of the LCA study the outcomes of the analysis done in the inventory phase together with the results from the impact analysis are considered (ISO 14040:2006(E)). In this phase the results' consistency and alignment with the defined goals and scope of the study are checked and evaluated (GaBi Software, 2009). According to ISO 14040 (2006(E)) these results must reach conclusions, explain limitations and provide recommendations.

The outcome of the interpretation phase is intended to give an understandable and comprehensive presentation of the findings of the LCA study that are consistent with the defined goals and scope. It should be noted that the goals and scope of the study, together with the data collected, may also be iteratively reviewed and modified within this phase. (ISO 14040:2006(E))

According to GaBi Software (2009) this phase includes two primary steps; the first step is identification of significant issues and the second step is evaluation which must take all stakeholders roles and responsibilities into account and reflect all findings in the presentation.

4.6 Critical review

A critical review is a requirement by ISO standards for all LCA studies conducted, to provide verification of whether the study and the methods used within the study are in accordance with the given ISO principles (ISO 14040:2006(E)) (GaBi Software, 2009). The critical review is included in the LCA report (ISO 14040:2006(E)). It shows whether requirements have been met concerning the methodology, data, interpretation and reporting (ISO 14040:2006(E)). According to GaBi Software (2009) the review also ensures quality of the study concerning the following aspects:

- LCA methods are consistent with the ISO standards;
- Data are appropriate and reasonable in reference to the defined goals;
- Limitations are stated and described;

- Assumptions are described; and
- Report is transparent and consistent

In general the critical review will assist in the understanding of all involved parties, providing confidence in the credibility of the LCA study (ISO 14040:2006(E)).

It should be noted that for this project a software program, GaBi Education, has been used. Thus the steps described in this chapter are built into the processing system of the software and will not be executed in the exact sequence.

5. Methodology

For this project the Educational version of GaBi software was used as a tool to execute a Life Cycle Assessment described in chapter 4. In this chapter the methodology used to apply GaBi as a tool to perform an LCA on the Brayton cycle, discussed in chapter 2 and chapter 3, is described in detail. The results of the LCA will be fully discussed in the following chapter.

5.1 Brayton cycle LCA using Educational version of GaBi software

The *Educational* version of GaBi software which was used to conduct an LCA for this project has some *limitations* which should be presented and discussed because of the nature of the influence on the LCA. The phases of an LCA study are now discussed, with reference to the limitations of the Educational version of GaBi used for this project.

5.1.1 Goal and scope definition

The goal of conducting the LCA is to determine the environmental effects the Brayton cycle of the SUNSPOT model has on the surrounding environment. The purpose and intended application of the study is to provide a reference and framework to the SUNSPOT project team to assist them in decision-making during the planning and development phase of the SUNSPOT project. The mechanical SUNSPOT project team members are thus the intended audience to whom the results are to be presented.

5.1.1.1 System boundaries

A Gate-To-Grave LCA study is conducted. This means that the study is conducted from the acquisition of the physical components, through the duration of the operation of the model plant to the grave of the system cycle and thus includes the disposal of the components. The extraction and raw material acquisition of natural gas, the manufacturing of the components and the transportation thereof are outside the scope of the conducted LCA. It also excludes material and energy exerted to construct the model plant before operation can start.

5.1.1.2 Data quality requirements:

Limited final parameter values and information could be retrieved from the mechanical engineers involved with the SUNSPOT model. Accordingly, many estimations, approximations and assumptions were made throughout this project. Although research was done and reasons provided for every estimation and approximation, the project is approached from an industrial engineering perspective, thus the methodological framework developed was more important than the actual values used. It is the responsibility of mechanical and chemical engineers to provide accurate (quality) data for the LCA and input into GaBi Software. This may be done at a later stage when the project is further in its development stage.

5.1.2 Inventory analysis

The database of the Educational version of GaBi has incomplete environmental, cost and technical data for many of the flows presented in the database. This means that many appropriate material flows chosen and inserted into GaBi with accurate quantities will show in the balancing results that the use of this material has no impact or environmental effect, which is not the case. For the purposes of this project some material flows that were less specific were in some cases chosen to able to ensure a rough estimation of environmental effects.

5.1.3 Impact analysis

When the SUNSPOT model is further developed by mechanical and chemical engineers, the full GaBi package with complete databases should be procured to present comprehensive results. For the purposes of this project the results and impact analysis will be further discussed and analyzed in more detail in chapter 6, section 6.2.

5.1.4 Interpretation phase

Accurate interpretation of the environmental effects of the Brayton cycle for the SUNSPOT model during its life cycle is improbable due to the many estimations and the lacking database (and thus poor data quality) of GaBi software. However, within the goal and scope defined in section 5.1.1, an accurate interpretation for the purposes of this project is made and discussed in chapter 6, section 6.3.

> **It should be noted that despite the limiting nature of the Educational version of GaBi software, a well-developed framework to conduct a comprehensive and complete LCA of the Brayton cycle in the SUNSPOT model has been modelled and presented. More accurate parameter estimations and calculations by mechanical and chemical engineers in a later stage of the development of the SUNSPOT model may simply be inserted into the model framework presented in this project.*

5.2 Methodology to create a project, a plan and processes in GaBi

Firstly a project database is created and activated within GaBi in which the modelling of the system will take place. Within this project all project plans, processes and flows are stored. The final project framework for the Brayton cycle can be seen in Appendix B.

Once a project database is created the processes containing inputs and outputs can be created. This represents the flow in the system. Six processes were created to be included into the project database; these processes as defined by section 3.1-3.6 are: Compressor, Solar receiver, Combustion chamber, Gas turbine, Generator and Thermal storage facility. The input and output flows to these processes are discussed below in section 5.3.

A plan of the model is created in which a physical representation of the process system as a whole may be viewed, including all connecting processes, flows and their quantities. The flows and their quantities may be selected to be displayed in various different units on the model plan according to the preference of the user. The energy (MJ), mass (kg) and reference quantities of the flows are viewed for the Brayton model project plan; they are displayed in Appendix C.

5.3 Methodology to create and insert input/output flows to processes in GaBi

The inputs and outputs to processes represent the flow in the system. When the output flow from one process is the input flow to another process these flows are referred to as the connecting flows and must be marked with an "X" within GaBi to show that they must be tracked. If an output flow is considered to be waste flow of the process, it must be marked with an "*". Each Brayton cycle process with its input/output flows inserted into GaBi is depicted in Appendix D. The tracked flows link the various processes with each other; this may be seen on the project plan shown in Appendix C.

It is important to note that all values used as input/output quantities in the GaBi model are determined for a *one second time period*. As a result mass/energy is determined per second and then inserted into GaBi as only the mass/energy value. This is mainly to ensure flow uniformity and consistency. Flows used in this process cycle are:

- Working fluid mass flow (kg/s) – given in section 2.3 and further calculated in section 3.3.2.
- Pipe/component material mass flow (kg/s) – discussed and calculated in this section, subsection 5.3.1
- Energy input/output flow (MJ/s) – calculated in chapter 3 and summarised in this section, subsection 5.3.2
- Power flows (MJ/s) - calculated in chapter 3 and summarised in this section, subsection 5.3.3

5.3.1 Component and pipe material flow

The mass of the components and the pipes was calculated in chapter 2 and chapter 3. It is assumed that at the end of the plant life the pipes and components will be written off as waste and a completely new plant will need to be constructed. To determine the effects of this waste over the entire life cycle of the model plant, which according to Harper (2010) is 25 years, the mass of the pipe/component is divided up and spread over the plant life. Thus the calculated mass per second (kg/s) material is seen as waste (kg) being emitted to the surroundings each second (s) of the plant life. This forms the basis of the pipe/component mass input flow and material mass output flow (waste) in GaBi. Using each components mass calculated in previous sections and summarised below, the mass flow of each pipe/component for every process is calculated in the following subsections.

Pipe/Component	*Section*	*Mass (kg)*
Compressor	3.1.5	150 000
Pipe – compressor to receiver / receiver to combustion chamber	2.4.3.1	131 683
Combustion chamber	3.3.4	5 000
Pipe – combustion chamber to turbine	2.4.3.2	1 316.83
Gas turbine	3.5.3	280 000
Generator	3.4	387 000
Pipe – turbine to thermal storage facility	2.4.3.3	3 668.31
Thermal storage facility	3.6.2	20 000 000

Table 7 Summary of pipe/components mass

5.3.1.1 Compressor

The material mass flow of the compressor is calculated to be:

$$\frac{150\ 000\ kg}{25\ years * 365.25\ days * 24\ hours * 60\ min * 60\ seconds}$$

$$= 190.128 * 10^{-6}\ \frac{kg}{s}$$

5.3.1.2 Solar receiver

The mass flow of the pipe between the compressor and solar receiver is inserted into GaBi as an inflow to the solar receiver process and a waste outflow from the receiver process, calculated as follows:

$$\frac{131\ 683\ kg}{25\ years * 365.25\ days * 24\ hours * 60\ \mathrm{min} * 60\ seconds}$$

$$= 166.91 * 10^{-6}\ \frac{kg}{s}$$

5.3.1.3 Combustion chamber

The mass flow of the pipe between the solar receiver and the combustion chamber is inserted into GaBi as an inflow to the combustion chamber and a waste outflow to this process, this is equal to previous mass flow calculated in section 5.4.2, 166.91 * $10^{-6}\,\frac{kg}{s}$.

Also the material mass flow of the combustion chamber is calculated to be:

$$\frac{5\ 000\ kg}{25\ years * 365.25\ days * 24\ hours * 60\min * 60\ seconds}$$

$$= 6.338 * 10^{-6}\ \frac{kg}{s}$$

5.3.1.4 Gas turbine

The mass flow of the pipe between the combustion chamber and turbine is inserted into GaBi as an inflow to the gas turbine process and a waste outflow from this process, calculated as follows:

$$\frac{1\ 316.83\ \ kg}{25\ years * 365.25\ days * 24\ hours * 60\min * 60\ seconds}$$

$$= 1.669 * 10^{-6}\ \frac{kg}{s}$$

The material mass flow of the gas turbine is calculated to be:

$$\frac{280\ 000\ kg}{25\ years * 365.25\ days * 24\ hours * 60\min * 60\ seconds}$$

$$= 354.91 * 10^{-6}\,\frac{kg}{s}$$

5.3.1.5 Generator

The material mass flow of the generator is calculated to be:

$$\frac{387\ 000\ kg}{25\ years * 365.25\ days * 24\ hours * 60\min * 60\ seconds}$$

$$= 490.532 * 10^{-6} \frac{kg}{s}$$

Mass per second for each separate material:

- Cast iron:

  $490.531 * 10^{-6} \frac{kg}{s} * 35\% = 171.686 * 10^{-6} \frac{kg}{s}$
- Carbon steel:

  $490.531 * 10^{-6} \frac{kg}{s} * 40\% = 196.212 * 10^{-6} \frac{kg}{s}$
- Copper wire:

  $490.531 * 10^{-6} \frac{kg}{s} * 25\% = 122.632 * 10^{-6} \frac{kg}{s}$

5.3.1.6 Thermal storage facility

The mass flow of the pipe between the turbine and the thermal storage facility is inserted into GaBi as an inflow to the thermal storage facility process and a waste outflow from this process, calculated as follows:

$$\frac{3\,668.312\ kg}{25\ years * 365.25\ days * 24\ hours * 60\min * 60\ seconds}$$

$$= 4.649 * 10^{-6} \frac{kg}{s}$$

The material mass flow of the thermal storage facility is calculated to be:

$$\frac{20\,000\,000\ kg}{25\ years * 365.25\ days * 24\ hours * 60\min * 60\ seconds}$$

$$= 25.350 * 10^{-3} \frac{kg}{s}$$

5.3.2 Energy input and output flow

Energy which the working fluid possesses at specific points during the process cycle, such as the inlet or outlet to a component, has already been calculated in chapter 3 of this project. The energy which the working fluid possesses at the inlet/outlet is inserted and considered in GaBi as an energy input/output flow to a process. These quantities are summarised in table 8 below.

Process	*Section*	*Input Energy (MJ)*	*Output Energy (MJ)*	*Waste heat/energy (MJ) per second (s)*
Compressor	3.1.4	127.20	289.96	6.42
Solar receiver	3.2.3	289.96	597.05	13.9
Combustion chamber	3.3.3	601.00	792.03	N/A
Gas turbine	3.5.2	792.03	369.46	133.93
Generator	3.4	-	-	2.1
Thermal storage facility	3.6.1	369.46	359.89	9.57

Table 8 Summary of processes input/output energy flows of working fluid

5.3.3 Power flows

In GaBi, power (energy per second) that a component is able to transfer to the next component or the power that is needed for a component to be driven by the previous component, are considered to be ‘power flows’. When entering power flows into GaBi the power unit of MW is entered as MJ because a one second time frame period is considered for the power plant. These ‘power flows’ are summarised in table 9 below.

Process	*Section*	*Input Power (MW)*	*Output Power (MW)*
Compressor	3.1.2	158	151.58
Solar receiver	3.2.1	278	264.10
Combustion chamber		-	-
Gas turbine	3.5.1	361.97	228.04
Generator	3.4	70.04	67.94
Thermal storage facility	-	-	-

Table 9 Input/output ‘power flows’ in the Brayton cycle

6. Results

The previous chapter discussed the methodology used to conduct an LCA on the Brayton cycle using GaBi software. It summarised the input/output flow values calculated and accumulated in chapter 2 and chapter 3, and how these values have been inserted into GaBi processes to form the whole connecting process model. This chapter focuses on presenting and discussing the results of the LCA.

6.1 The Results of the LCA

The results obtained from the LCA in GaBi are the environmental impact values measured for every *input* and *output flow* of the Brayton cycle system over its operational life (and disposal) for each impact category. Impact categories group different emissions into a quantified measure on the effect on the environment, using a scientific approach to quantification which is universally applicable (De Keulenaer, 2006). The *Impact Potential* is a substance's contribution to the impact measured relative to the impact of a major substance (De Keulenaer, 2006).

GaBi provides detailed environmental impact value results for the *input flows* and *output flows* separately; these are shown in Appendix E and Appendix F respectively. GaBi also provides the values of the input flows *balanced* with the output flows, to show the net environmental impacts of the flows; this may be seen in Appendix G. For the purpose of this project the applicable environmental impact categories that have the most significant influence and their values are extracted from Appendix G and summarised in table 10 below.

Environmental Quantities: ***Impact Category***	***Impact Potential***	***Units***
1. Abiotic Depletion Potential (ADP)	123.359×10^{-3}	kg Sb-Equiv
2. Abiotic Depletion Potential (ADP fossil)	256.463	MJ
3. Eutrophication Potential (EP)	135.829	kg Phosphate-Equiv
4. Global Warming Potential (GWP 100 years)	16.090	kg CO_2-Equiv

Table 10 Net environmental impacts of the balanced input/output flows of the Brayton cycle

In the Brayton cycle the greatest cause of the impacts categorised in table 10 above is emissions to air, see the graph (Fig 12) below. The combustion of natural gas (methane) in air produces nitrogen, carbon dioxide and oxygen which are then released into the air through the thermal storage facility outlet. Nitrogen and carbon dioxide are classified as inorganic emissions, while oxygen is an organic emission. The heavy metal emission to air accounts for all component/pipe material of each process (which is seen as waste per second as discussed in section 5.3.1) that will be disposed of after the plant life. The graph (Fig. 13) below shows how much heavy metal waste the processes cause relative to each other. Although from the graph (Fig. 13) it is clear that the gas turbine has the greatest heavy metal waste contribution out of all the processes, figure 12 shows that the effect of this waste is small enough to be considered negligible. The impacts these emissions have on the environment will now be discussed.

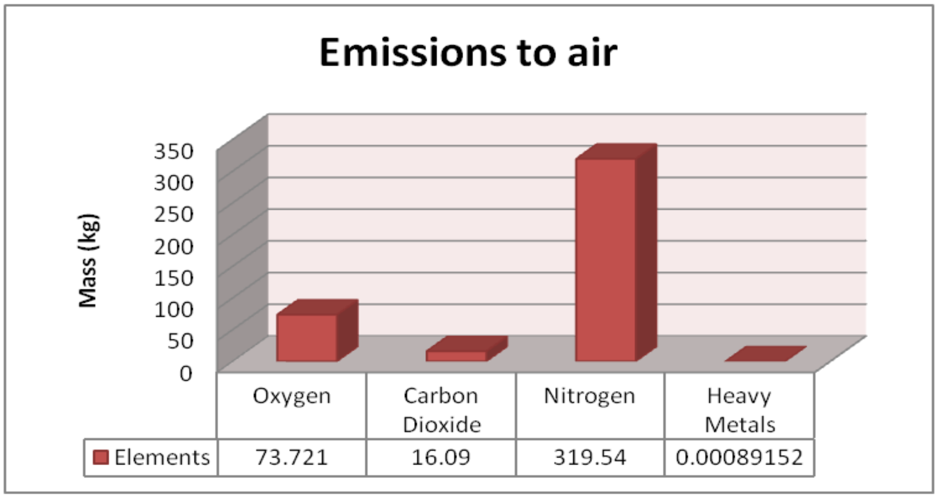

Figure 12 Total emissions to air from the Brayton cycle processes

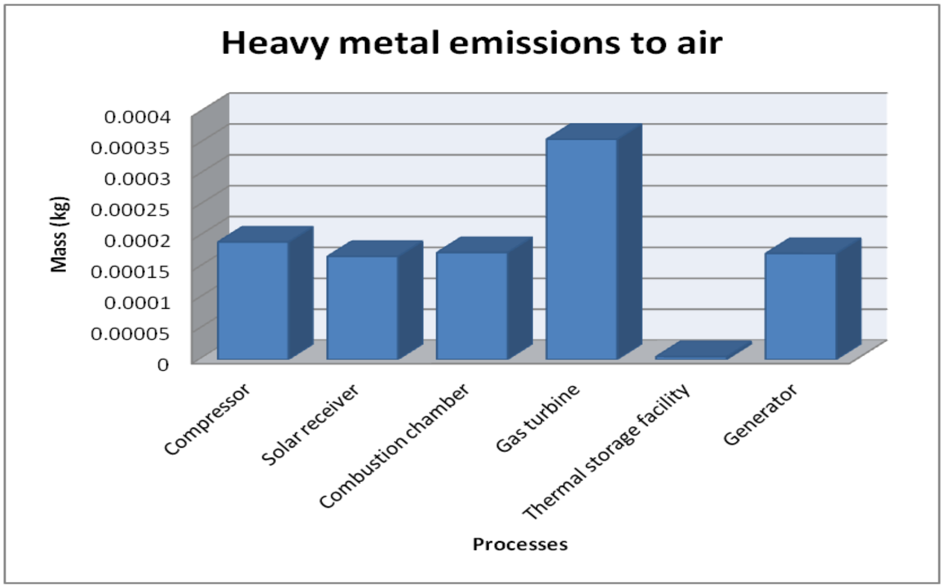

Figure 13 Heavy metal emissions to air from the Brayton cycle processes

6.2 Impact Analysis: Environmental effects

The three environmental impact categories which have the most significant contribution to environmental effects caused by the Brayton cycle process and its sub-processes are: Abiotic Depletion, Eutrophication and Global Warming. These three environmental effects are now discussed further in detail.

6.2.1 Abiotic Depletion Potential (ADP)

The indicator for abiotic depletion is the decrease in resource availability (Oers, de Koning, Guinèe and Huppes, 2002). The most significant type of abiotic resources identified in the Brayton cycle is referred to as deposit.

Deposits refer to resources that cannot be regenerated, such as the natural gas used in combustion or non-renewable material resource such as the copper used in the generator (Oers, de Koning, Guinèe and Huppes, 2002). No 1 in table 9, abiotic depletion measured in kg Antimony (Sb) equivalents, represents the environmental impact of the decrease in availability of natural gas and copper as resource. The impact potential no 2 in table 9, abiotic depletion ADP fossil measured in MJ, measures the decrease in useable energy available because of the combustion of natural gas.

6.2.2 Eutrophication Potential (EP)

Excess nutrients injected into the aquatic or terrestrial environment are referred to as eutrophication (GaBi software, 2009). This may cause a disruption in the biodiversity of the environment. It mainly originates from nitrogen and phosphorus emissions into the surroundings, although air pollutants and waste water contribute (GaBi software, 2009). In table 9 no 3 is the EP caused by inorganic emissions to air; nitrogen (N_2) and carbon dioxide (CO_2) formed during combustion and eventually released into the air. This is measured in kg Phosphate-Equiv.

Comparing the various systems' EP with each other is meaningless because the eutrophication potential differs regionally (GaBi software, 2009).

6.2.3 Global warming Potential (GWP)

Carbon dioxide (CO_2) is one of the greenhouse gas (GHG) emissions that retain heat within the earth's atmosphere, which results in global warming. As already discussed in section 1.1, the rate of global warming and its negative environmental effects are increasing exponentially. The graph (Fig. 13) depicts the CO_2 emitted to the air during the Brayton cycle process. The result of this emission is given by table 9 no 4 as the global warming potential (GWP) for a time range of 100 years measured in kg CO_2 equivalents. The GWP is an index to measure the contribution to global warming of a substance that is released into the atmosphere (GaBi software, 2009).

6.3 Interpretation Phase: Comparative results

The GWP is the indicator of the most significant environmental impacts of the Brayton cycle, thus the CO_2 emissions of the power plant are compared with other power plant technology types. The hybrid combined cycle solar power plant has a total power output of 275.04 MW (Thirion, 2011). The total CO_2 emission as depicted in the graph (Fig. 13), 16.09 kg each second, is due to the natural gas combusted in the Brayton cycle. The effects have already been discussed above in section 6.2.2 and section 6.2.3. The Rankine cycle, which is the steam turbine that follows using the Brayton cycle's exhaust heat, has negligible CO_2 emissions (Thirion, 2011). Thus the total kg CO_2 emission per MWh for the plant is:

$$\frac{16.09\,\frac{kg}{s}\,CO_2\,*\,3600\,\frac{s}{h}}{275.04\,MW.h}$$

$$= 210.602 \text{ kg-}CO_2\text{/MWh}$$

When this value is compared to the values of several fossil fuelled power plants, as summarised below in table 11, it is clear that hybrid solar combined cycle power plant has much lower carbon dioxide emissions than conventional fossil fuel power plants. It has approximately two and a half times less CO_2 emissions than a natural gas fired power plant and up to five times less than conventional coal power plant. Notably, unlike solo solar thermal power plants, the carbon emissions are not small enough to be seen as negligible.

Power plant - resource	*kg-CO_2/MWh*
Oil	758.406
Coal	1 020.129
Natural gas	514.827

Table 11 Fossil fuel power plants' CO_2 emissions per megawatt hour

Source: *Clean Energy – Air emissions, 2000*

Although this value is much lower than for conventional fossil fuelled power plants, it should be mentioned that all CO_2 emissions come from the 25% energy contribution that methane adds to the system during combustion, as seen in figure 15 below. This should be taken into consideration during the further design stages of the SUNSPOT model, to ensure an optimized balance between the minimum amount of fuel (and its contributing energy) necessary to maintain desired power output versus the amount of CO_2 emissions it produces.

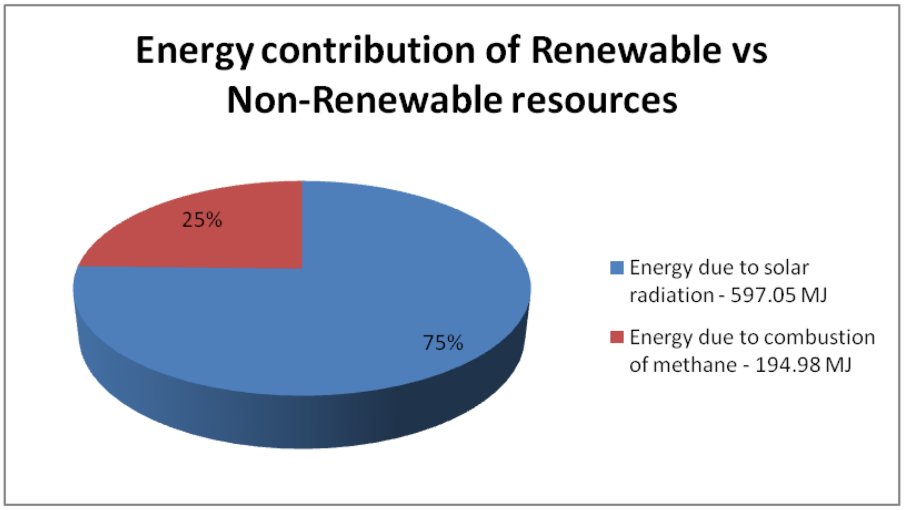

Figure 14 The energy contribution of the renewable and non-renewable resources

7. Conclusions

Solar energy is a promising contributor to the energy demands of the future because of its clean, abundant and renewable nature. In the SUNSPOT hybrid solar central receiver power plant model discussed in this project, natural gas was used during combustion in the Brayton cycle. This is the only aspect of the power plant emitting CO_2 into the air.

A LCA was done using GaBi software to determine the environmental impact which the Brayton cycle has on the environment in comparison with fossil fuel powered plants. The LCA was done for the operational life and disposal phases of the system life cycle. Given the appropriate databases in GaBi, the software takes into account all inputs and outputs that are involved in the entire Brayton cycle process. The *Educational* version of GaBi software which was used for the purposes of this project has displayed some limitations. The most significant limitation is the fact that the inventory database is incomplete. This places a restriction on the accuracy and usability of the results. It should be noted that despite the limiting nature of the Educational version of GaBi software, a well-developed framework to conduct a comprehensive and complete LCA of the Brayton cycle in the SUNSPOT model has been modelled and presented.

This LCA forms the basis on which further assessments and more extensive LCAs can be done. Surety of validation and verification of data is necessary before these LCA results can be used; this is because many estimations, assumptions and approximations were made concerning data about the SUNSPOT model, because data was not yet readily available. In this LCA, however, the results obtained from GaBi are environmental impact values measured for each impact category. The environmental impact categories that have the most significant influence were presented and discussed. These were found to be abiotic depletion potential (ADP), eutrophication potential (EP) and global warming potential (GWP). It was shown that although nitrogen and then oxygen are the two largest emissions to air, carbon dioxide has the most significant environmental impact because of its contribution to global warming.

Taking all this into account, the conclusion is drawn that combined cycle operations are more efficient than those of single cycles. The Brayton cycle plays a specific key role in implementing solar technologies in conventional fossil fuel power plants. Although a fossil fuel (natural gas) is still used during the operation of the power plant, the CO_2 emissions of the hybrid power plant are significantly lower than for pure conventional fossil fuelled power plants. This is a more sustainable and cleaner power generation option, playing a significant contributing role in environmental impact relief.

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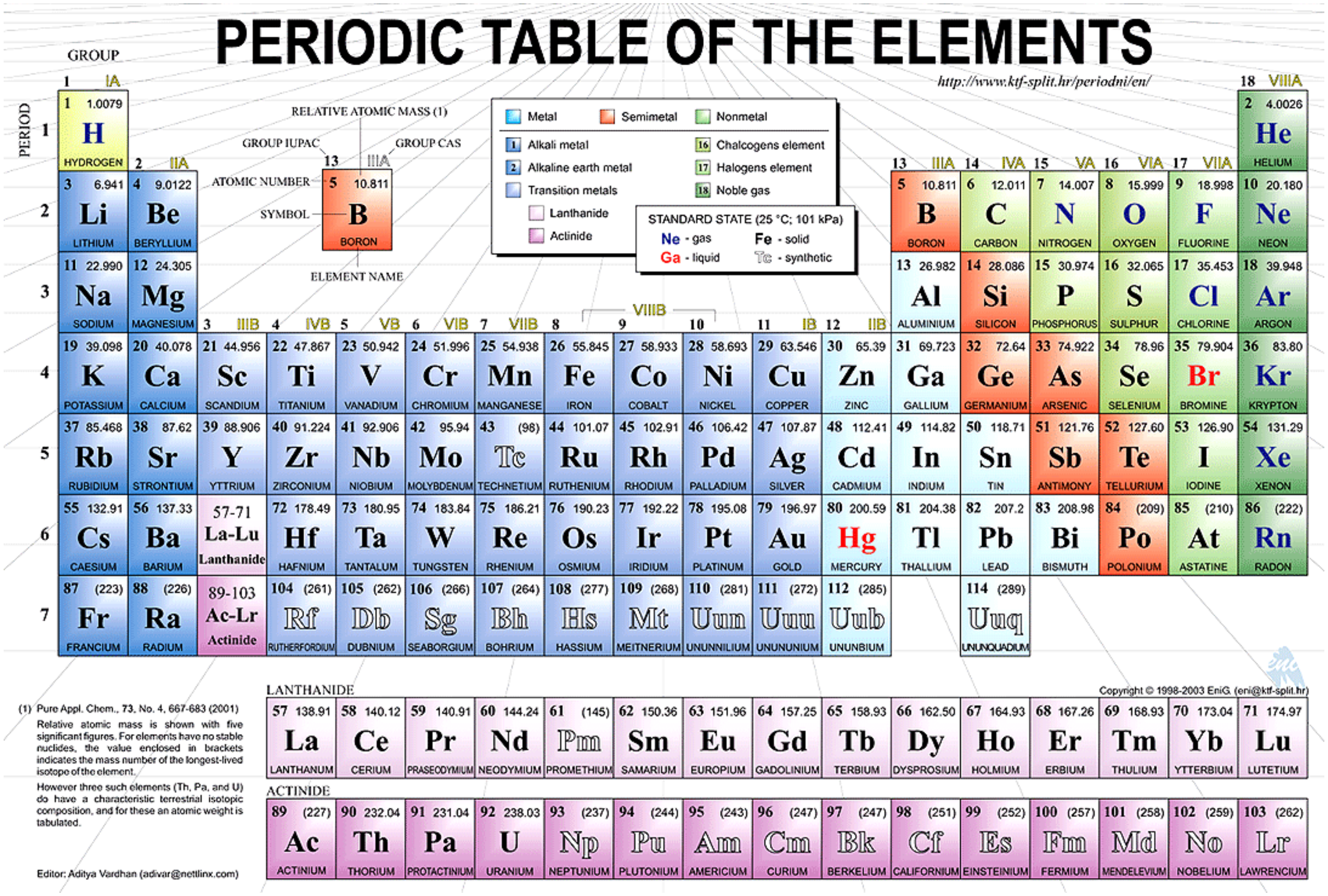
Appendix A Periodic Table



PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

PERIOD	GROUP 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNILIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

RELATIVE ATOMIC MASS (1)
GROUP IUPAC 13
GROUP CAS IIIA
ATOMIC NUMBER 5
10.811
SYMBOL B
ELEMENT NAME BORON

- 🟦 Metal
- 🟥 Semimetal
- 🟩 Nonmetal
- 1 Alkali metal
- 2 Alkaline earth metal
- Transition metals
- Lanthanide
- Actinide
- 16 Chalcogens element
- 17 Halogens element
- 18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Ga - liquid
Fe - solid
Tc - synthetic

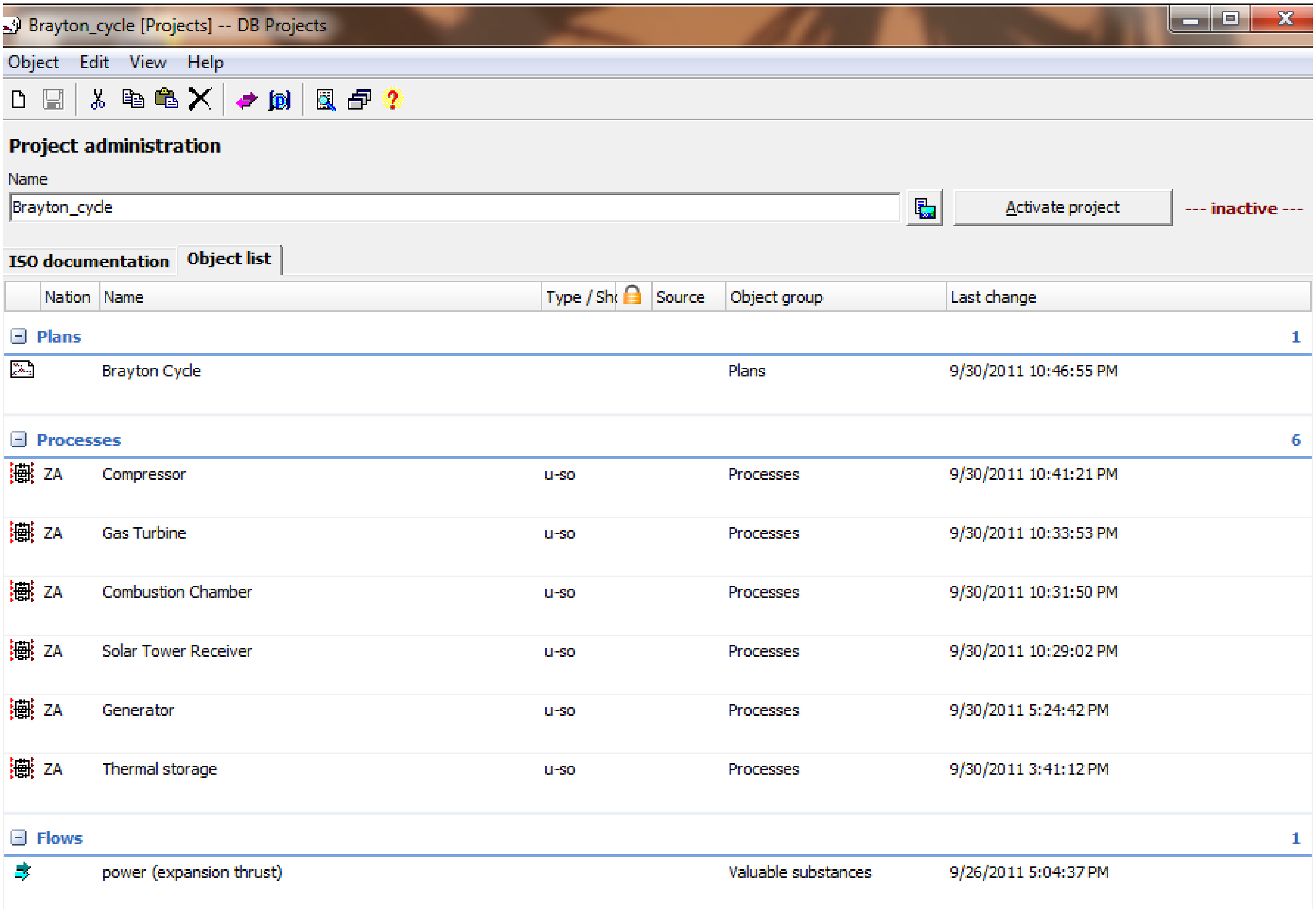
(1) Pure Appl. Chem., **73**, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@netlinx.com)

Appendix B GaBi Project Framework



Project administration

Name: Brayton_cycle

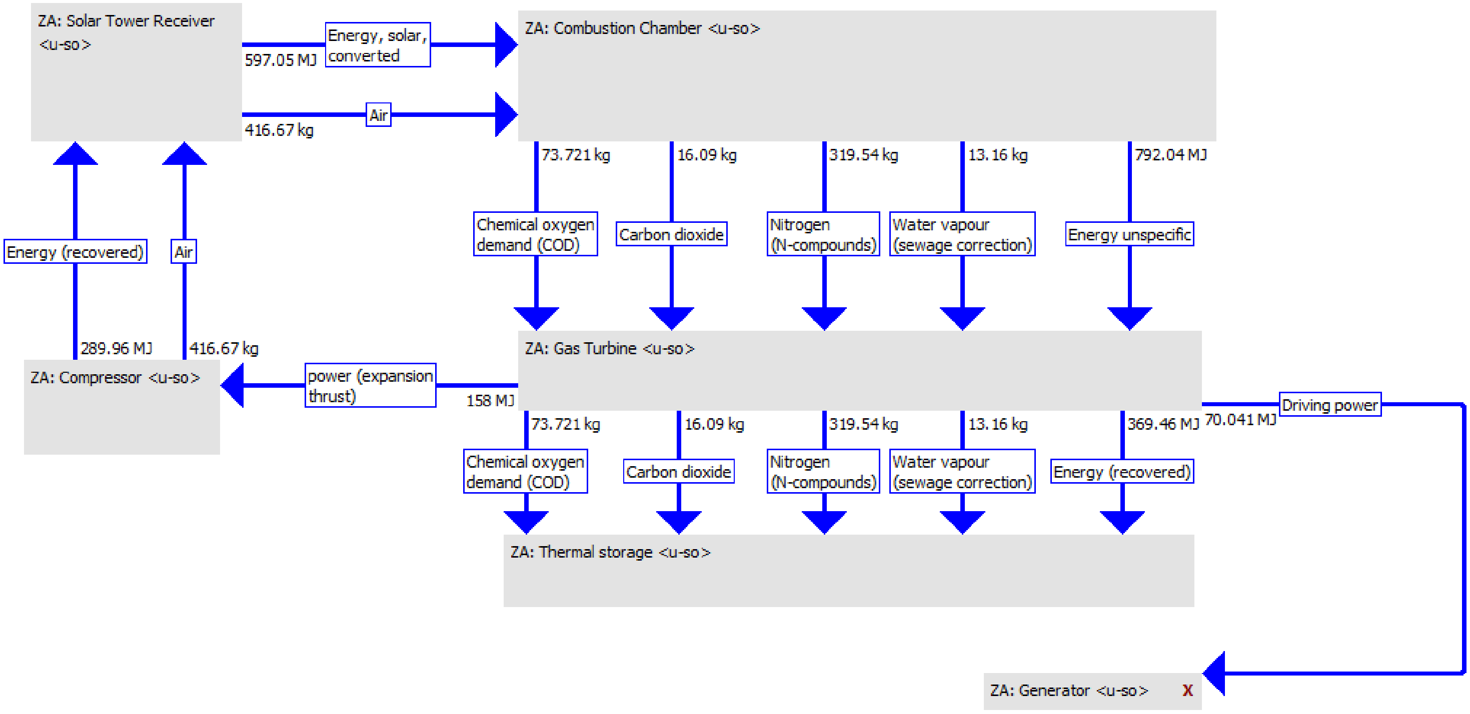
--- inactive ---

Nation	Name	Type / Sh	Source	Object group	Last change
Plans					**1**
	Brayton Cycle			Plans	9/30/2011 10:46:55 PM
Processes					**6**
ZA	Compressor	u-so		Processes	9/30/2011 10:41:21 PM
ZA	Gas Turbine	u-so		Processes	9/30/2011 10:33:53 PM
ZA	Combustion Chamber	u-so		Processes	9/30/2011 10:31:50 PM
ZA	Solar Tower Receiver	u-so		Processes	9/30/2011 10:29:02 PM
ZA	Generator	u-so		Processes	9/30/2011 5:24:42 PM
ZA	Thermal storage	u-so		Processes	9/30/2011 3:41:12 PM
Flows					**1**
	power (expansion thrust)			Valuable substances	9/26/2011 5:04:37 PM

Appendix C GaBi Project Plan

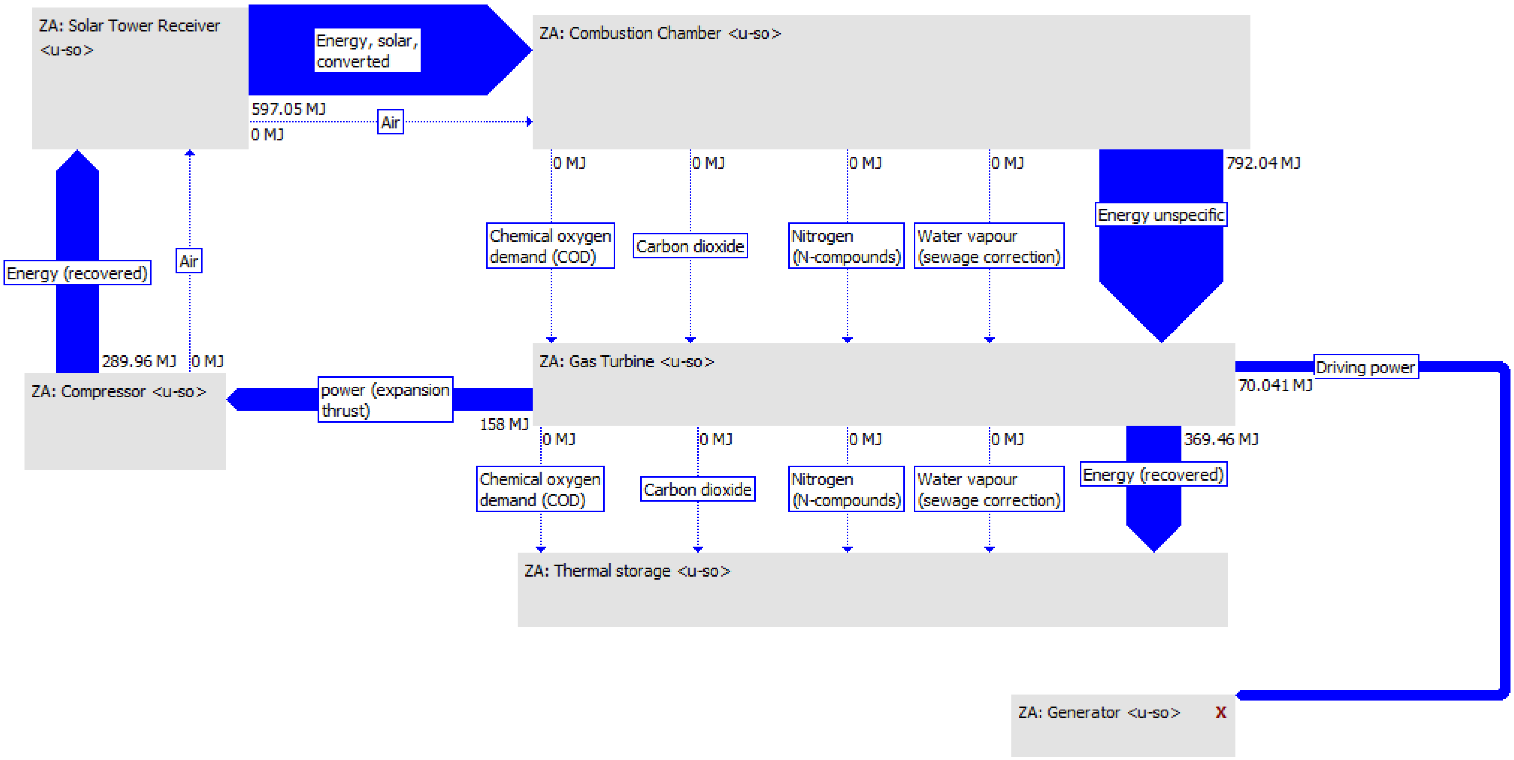
Brayton Cycle

GaBi 4 process plan:Reference quantities
The names of the basic processes are shown.



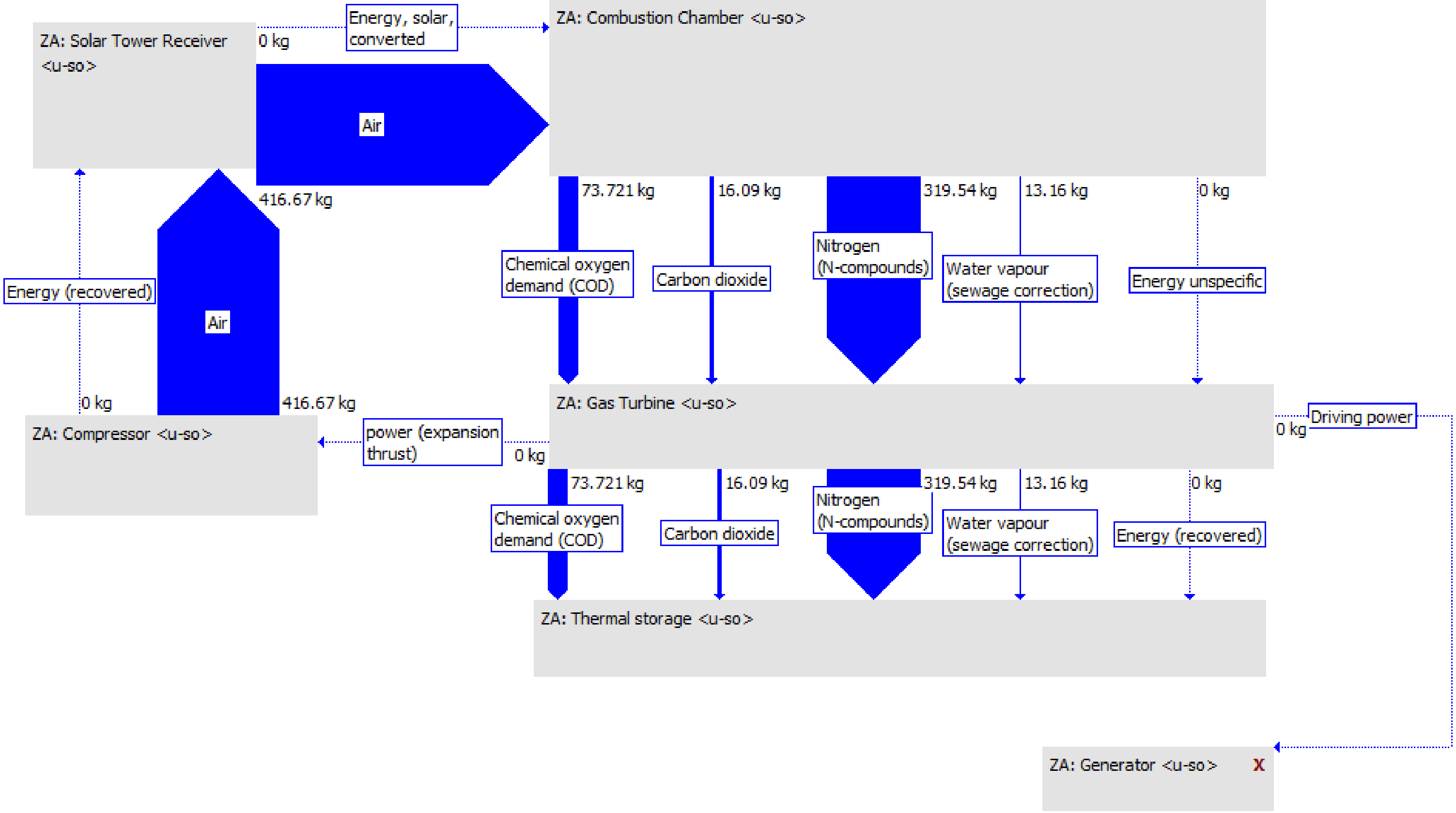
Brayton Cycle

GaBi 4 process plan: Energy (net calorific value) [MJ]
The names of the basic processes are shown.

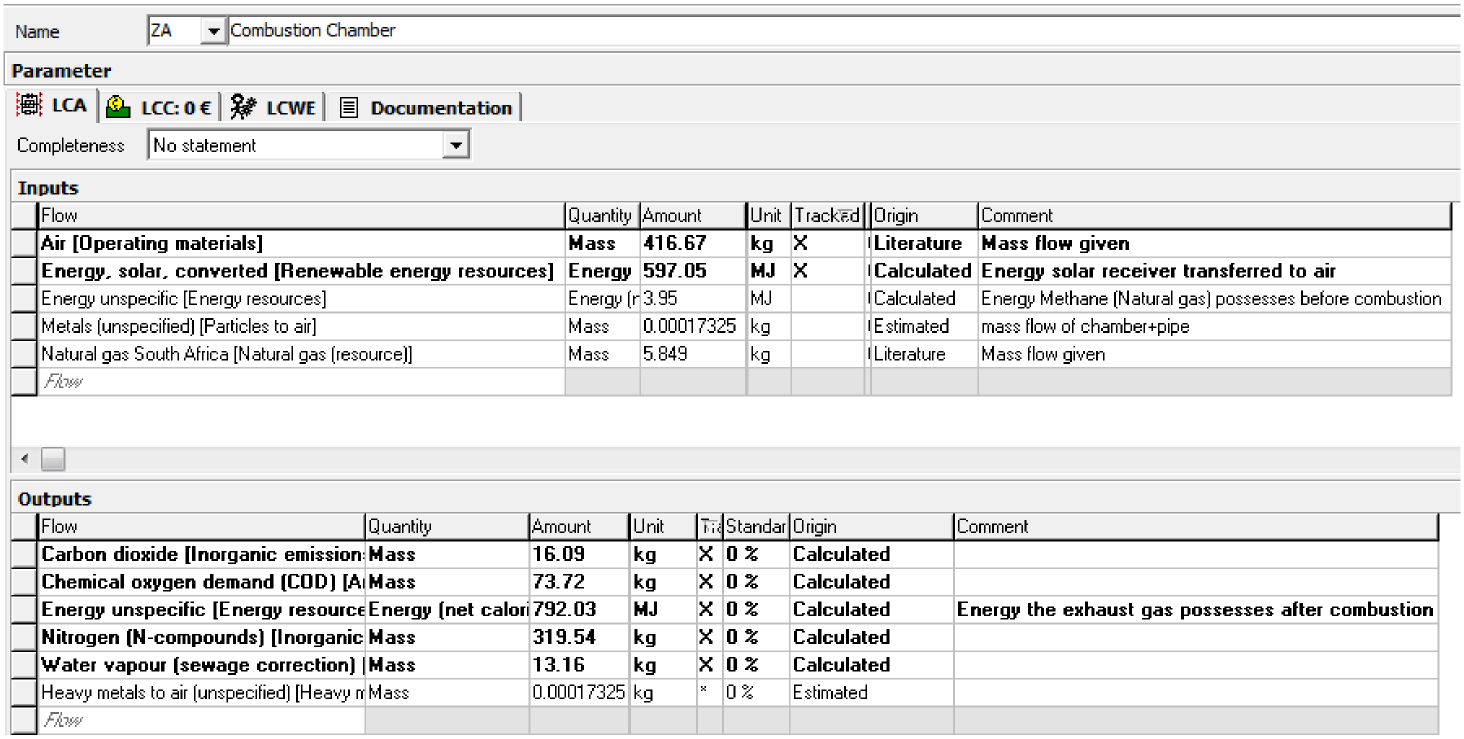


Brayton Cycle

GaBi 4 process plan: Mass [kg]
The names of the basic processes are shown.



Appendix D Brayton cycle processes and flows in GaBi



Name ZA Combustion Chamber

Parameter

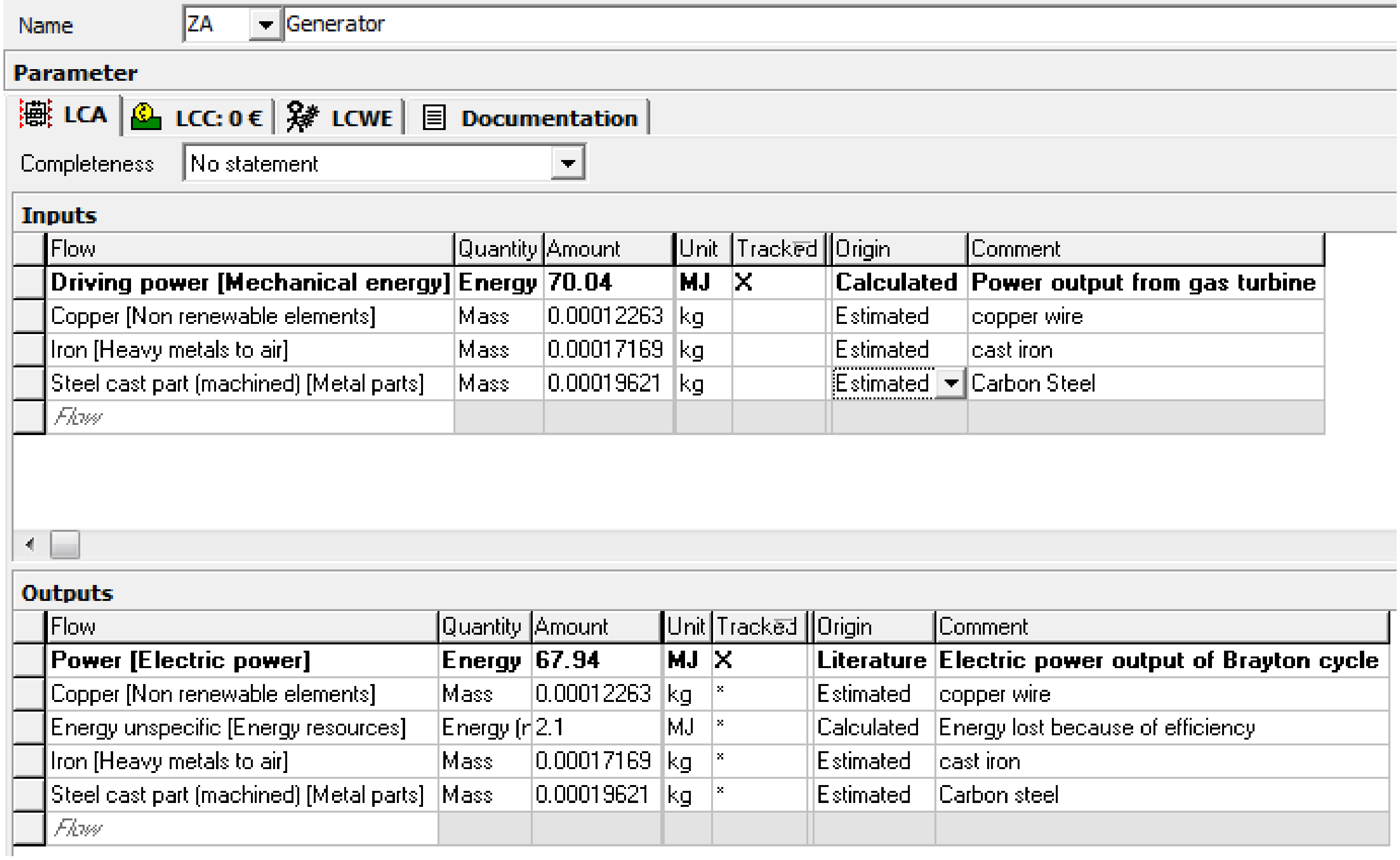
Completeness: No statement

Inputs

Flow	Quantity	Amount	Unit	Tracked	Origin	Comment
Air [Operating materials]	**Mass**	**416.67**	**kg**	**X**	**Literature**	**Mass flow given**
Energy, solar, converted [Renewable energy resources]	**Energy**	**597.05**	**MJ**	**X**	**Calculated**	**Energy solar receiver transferred to air**
Energy unspecific [Energy resources]	Energy (r	3.95	MJ		Calculated	Energy Methane (Natural gas) possesses before combustion
Metals (unspecified) [Particles to air]	Mass	0.00017325	kg		Estimated	mass flow of chamber+pipe
Natural gas South Africa [Natural gas (resource)]	Mass	5.849	kg		Literature	Mass flow given
Flow						

Outputs

Flow	Quantity	Amount	Unit	Tra	Standar	Origin	Comment
Carbon dioxide [Inorganic emission	**Mass**	**16.09**	**kg**	**X**	**0 %**	**Calculated**	
Chemical oxygen demand (COD) [A	**Mass**	**73.72**	**kg**	**X**	**0 %**	**Calculated**	
Energy unspecific [Energy resource	**Energy (net calori**	**792.03**	**MJ**	**X**	**0 %**	**Calculated**	**Energy the exhaust gas possesses after combustion**
Nitrogen (N-compounds) [Inorganic	**Mass**	**319.54**	**kg**	**X**	**0 %**	**Calculated**	
Water vapour (sewage correction) [	**Mass**	**13.16**	**kg**	**X**	**0 %**	**Calculated**	
Heavy metals to air (unspecified) [Heavy m	Mass	0.00017325	kg	*	0 %	Estimated	
Flow							



Name ZA Generator

Parameter

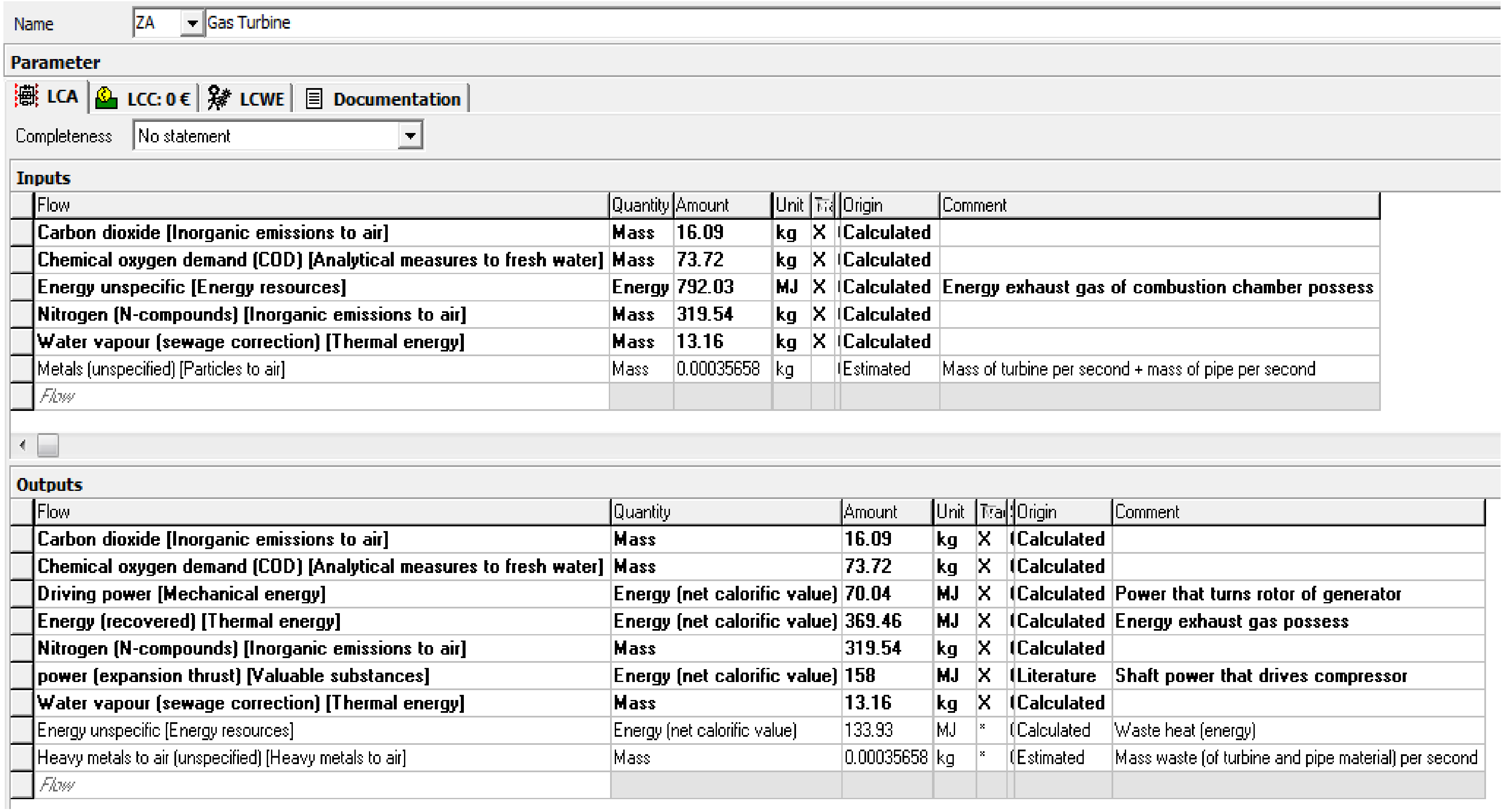
Completeness: No statement

Inputs

Flow	Quantity	Amount	Unit	Tracked	Origin	Comment
Driving power [Mechanical energy]	**Energy**	**70.04**	**MJ**	**X**	**Calculated**	**Power output from gas turbine**
Copper [Non renewable elements]	Mass	0.00012263	kg		Estimated	copper wire
Iron [Heavy metals to air]	Mass	0.00017169	kg		Estimated	cast iron
Steel cast part (machined) [Metal parts]	Mass	0.00019621	kg		Estimated	Carbon Steel
Flow						

Outputs

Flow	Quantity	Amount	Unit	Tracked	Origin	Comment
Power [Electric power]	**Energy**	**67.94**	**MJ**	**X**	**Literature**	**Electric power output of Brayton cycle**
Copper [Non renewable elements]	Mass	0.00012263	kg	*	Estimated	copper wire
Energy unspecific [Energy resources]	Energy (r	2.1	MJ	*	Calculated	Energy lost because of efficiency
Iron [Heavy metals to air]	Mass	0.00017169	kg	*	Estimated	cast iron
Steel cast part (machined) [Metal parts]	Mass	0.00019621	kg	*	Estimated	Carbon steel
Flow						



Name ZA Gas Turbine

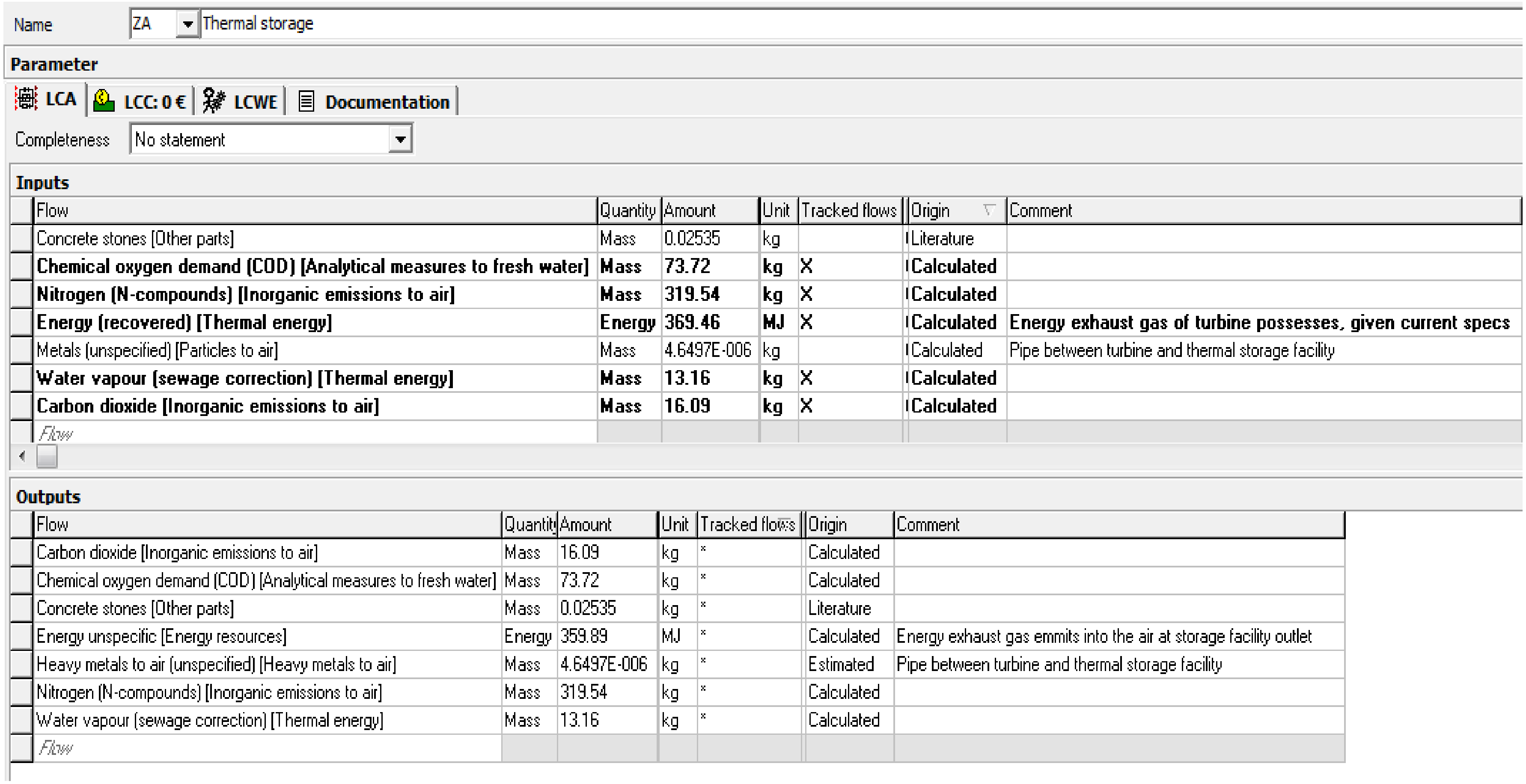
Completeness No statement

Inputs

Flow	Quantity	Amount	Unit	Tra	Origin	Comment
Carbon dioxide [Inorganic emissions to air]	**Mass**	**16.09**	**kg**	X	**Calculated**	
Chemical oxygen demand (COD) [Analytical measures to fresh water]	**Mass**	**73.72**	**kg**	X	**Calculated**	
Energy unspecific [Energy resources]	**Energy**	**792.03**	**MJ**	X	**Calculated**	**Energy exhaust gas of combustion chamber possess**
Nitrogen (N-compounds) [Inorganic emissions to air]	**Mass**	**319.54**	**kg**	X	**Calculated**	
Water vapour (sewage correction) [Thermal energy]	**Mass**	**13.16**	**kg**	X	**Calculated**	
Metals (unspecified) [Particles to air]	Mass	0.00035658	kg		Estimated	Mass of turbine per second + mass of pipe per second
Flow						

Outputs

Flow	Quantity	Amount	Unit	Tra	Origin	Comment
Carbon dioxide [Inorganic emissions to air]	**Mass**	**16.09**	**kg**	X	**Calculated**	
Chemical oxygen demand (COD) [Analytical measures to fresh water]	**Mass**	**73.72**	**kg**	X	**Calculated**	
Driving power [Mechanical energy]	**Energy (net calorific value)**	**70.04**	**MJ**	X	**Calculated**	**Power that turns rotor of generator**
Energy (recovered) [Thermal energy]	**Energy (net calorific value)**	**369.46**	**MJ**	X	**Calculated**	**Energy exhaust gas possess**
Nitrogen (N-compounds) [Inorganic emissions to air]	**Mass**	**319.54**	**kg**	X	**Calculated**	
power (expansion thrust) [Valuable substances]	**Energy (net calorific value)**	**158**	**MJ**	X	**Literature**	**Shaft power that drives compressor**
Water vapour (sewage correction) [Thermal energy]	**Mass**	**13.16**	**kg**	X	**Calculated**	
Energy unspecific [Energy resources]	Energy (net calorific value)	133.93	MJ	*	Calculated	Waste heat (energy)
Heavy metals to air (unspecified) [Heavy metals to air]	Mass	0.00035658	kg	*	Estimated	Mass waste (of turbine and pipe material) per second
Flow						



Name ZA Thermal storage

Parameter

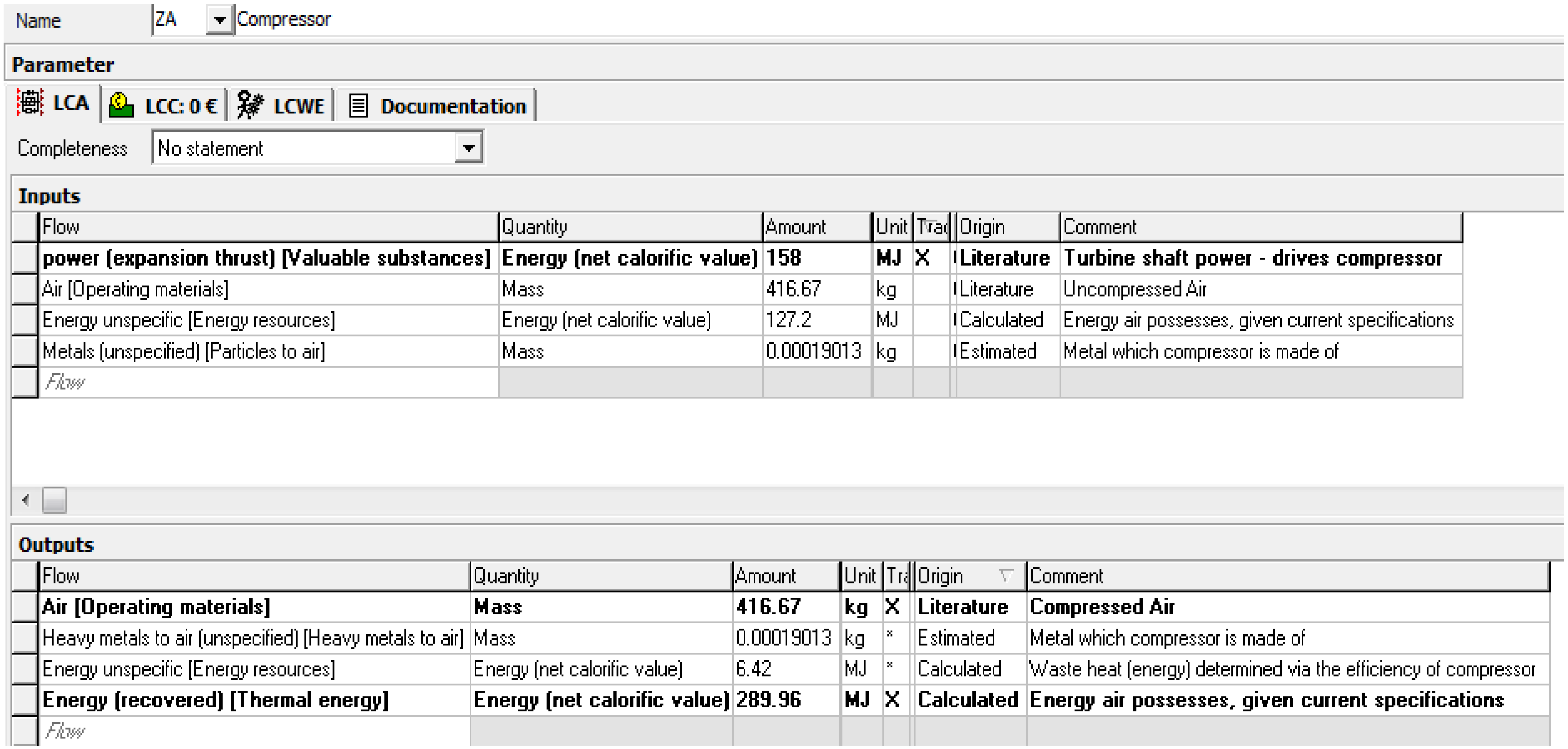
Completeness: No statement

Inputs

Flow	Quantity	Amount	Unit	Tracked flows	Origin	Comment
Concrete stones [Other parts]	Mass	0.02535	kg		Literature	
Chemical oxygen demand (COD) [Analytical measures to fresh water]	**Mass**	**73.72**	**kg**	**X**	**Calculated**	
Nitrogen (N-compounds) [Inorganic emissions to air]	**Mass**	**319.54**	**kg**	**X**	**Calculated**	
Energy (recovered) [Thermal energy]	**Energy**	**369.46**	**MJ**	**X**	**Calculated**	**Energy exhaust gas of turbine possesses, given current specs**
Metals (unspecified) [Particles to air]	Mass	4.6497E-006	kg		Calculated	Pipe between turbine and thermal storage facility
Water vapour (sewage correction) [Thermal energy]	**Mass**	**13.16**	**kg**	**X**	**Calculated**	
Carbon dioxide [Inorganic emissions to air]	**Mass**	**16.09**	**kg**	**X**	**Calculated**	
Flow						

Outputs

Flow	Quantity	Amount	Unit	Tracked flows	Origin	Comment
Carbon dioxide [Inorganic emissions to air]	Mass	16.09	kg	*	Calculated	
Chemical oxygen demand (COD) [Analytical measures to fresh water]	Mass	73.72	kg	*	Calculated	
Concrete stones [Other parts]	Mass	0.02535	kg	*	Literature	
Energy unspecific [Energy resources]	Energy	359.89	MJ	*	Calculated	Energy exhaust gas emmits into the air at storage facility outlet
Heavy metals to air (unspecified) [Heavy metals to air]	Mass	4.6497E-006	kg	*	Estimated	Pipe between turbine and thermal storage facility
Nitrogen (N-compounds) [Inorganic emissions to air]	Mass	319.54	kg	*	Calculated	
Water vapour (sewage correction) [Thermal energy]	Mass	13.16	kg	*	Calculated	
Flow						



Name ZA Compressor

Parameter

Completeness: No statement

Inputs

Flow	Quantity	Amount	Unit	Trad	Origin	Comment
power (expansion thrust) [Valuable substances]	**Energy (net calorific value)**	**158**	**MJ**	**X**	**Literature**	**Turbine shaft power - drives compressor**
Air [Operating materials]	Mass	416.67	kg		Literature	Uncompressed Air
Energy unspecific [Energy resources]	Energy (net calorific value)	127.2	MJ		Calculated	Energy air possesses, given current specifications
Metals (unspecified) [Particles to air]	Mass	0.00019013	kg		Estimated	Metal which compressor is made of
Flow						

Outputs

Flow	Quantity	Amount	Unit	Tra	Origin	Comment
Air [Operating materials]	**Mass**	**416.67**	**kg**	**X**	**Literature**	**Compressed Air**
Heavy metals to air (unspecified) [Heavy metals to air]	Mass	0.00019013	kg	*	Estimated	Metal which compressor is made of
Energy unspecific [Energy resources]	Energy (net calorific value)	6.42	MJ	*	Calculated	Waste heat (energy) determined via the efficiency of compressor
Energy (recovered) [Thermal energy]	**Energy (net calorific value)**	**289.96**	**MJ**	**X**	**Calculated**	**Energy air possesses, given current specifications**
Flow						

Appendix E GaBi INPUT Results

				Combustion Chamber	Compressor	Gas Turbine	Generator	Solar Receiver	Thermal Storage
1		**Environmental quantities**							
1.1	EDIP 1997, Resource quantities								
	1.1.1	EDIP 1997, Copper [kg]	0.000122634	0	0	0	0.0001226	0	0
1.2	CML2001								
	1.2.1	CML2001 - Dec. 07, Abiotic Depletion (ADP) [kg Sb-Equiv.]	0.123360052	0.12335981	0	0	2.38E-07	0	0
	1.2.5	CML2001 - Nov. 09, Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	1.68E-07	0	0	0	1.68E-07	0	0
	1.2.6	CML2001 - Nov. 09, Abiotic Depletion (ADP fossil) [MJ]	256.4630721	256.463072	0	0	0	0	0
	1.2.7	CML2001 - Nov. 09, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0	0	0	135.829618	0	0	135.829618
	1.2.8	CML2001 - Nov. 09, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0	0	0	16.0901158	0	0	16.09011585
	1.2.9	CML2001 - Nov. 09, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	0.000731047	0.00014206	0.000155906	0.0002924	0	0.00013687	3.81E-06
	1.2.10	CML2001, Abiotic Depletion (ADP) [kg Sb-Equiv.]	0.186443656	0.12525978	0.061183641	0.38096917	2.38E-07	0	0
	1.2.11	CML2001, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	0	0	0	135.829618	0	0	135.829618
	1.2.12	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	0	0	0	16.0901158	0	0	16.09011585
	1.2.13	CML2001, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	0.000731047	0.00014206	0.000155906	0.0002924	0	0.00013687	3.81E-06
1.3	CML96								
	1.3.1	CML96, Eutrification potential (EP) [kg Phosphate-Equiv.]	0	0	0	1.62185168	0	0	1.621851677
	1.3.2	CML96, Global warming potential (GWP 100 years) [kg CO2-Equiv.]	0	0	0	16.0901158	0	0	16.09011585
	1.3.3	CML96, Global warming potential (GWP 20 years) [kg CO2-Equiv.]	0	0	0	16.0901158	0	0	16.09011585
	1.3.4	CML96, Global warming potential (GWP 500 years) [kg CO2-Equiv.]	0	0	0	16.0901158	0	0	16.09011585
1.4	EDIP 1997								
	1.4.1	EDIP 1997, Ecotoxicity soil chronic [m3 soil]	0.09132028	0	0	0	0.0913203	0	0
	1.4.2	EDIP 1997, Ecotoxicity water chronic [m3 water]	3.433756683	0	0	0	3.4337567	0	0
	1.4.3	EDIP 1997, Global warming potential (GWP 100 years) [kg CO2-Equiv.]	0	0	0	16.0901158	0	0	16.09011585
	1.4.4	EDIP 1997, Human toxicity air [m3 air]	6370.606091	0	0	0	6370.6061	0	0
	1.4.5	EDIP 1997, Human toxicity soil [m3 soil]	0.132359507	0	0	0	0.1323595	0	0
	1.4.6	EDIP 1997, Human toxicity water [m3 water]	0.001654446	0	0	0	0.0016544	0	0
1.5	EDIP 2003								
	1.5.1	EDIP 2003, Global warming [kg CO2-Equiv.]	0	0	0	16.0901158	0	0	16.09011585
1.6	EI99								
	1.6.1	EI99, EA, Human health, Climate Change [DALY]	0	0	0	3.38E-06	0	0	3.38E-06
	1.6.2	EI99, EA, Human health, Respiratory (inorganic) [DALY]	3.34E-07	6.50E-08	7.13E-08	1.34E-07	0	6.26E-08	1.74E-09
	1.6.3	EI99, EA, Resources, Fossil fuels [MJ surplus energy]	22.82534644	22.8253464	0	0	0	0	0
	1.6.4	EI99, EA, Resources, Minerals [MJ surplus energy]	0.00450066	0	0	0	0.0045007	0	0
	1.6.5	EI99, HA, Human health, Climate Change [DALY]	0	0	0	3.38E-06	0	0	3.38E-06
	1.6.7	EI99, HA, Resources, Fossil fuels [MJ surplus energy]	38.46946081	38.4694608	0	0	0	0	0
	1.6.8	EI99, HA, Resources, Minerals [MJ surplus energy]	0.00450066	0	0	0	0.0045007	0	0
	1.6.9	EI99, IA, Human health, Climate Change [DALY]	0	0	0	3.22E-06	0	0	3.22E-06
	1.6.10	EI99, IA, Human health, Respiratory (inorganic) [DALY]	2.44E-07	4.75E-08	5.21E-08	9.77E-08	0	4.57E-08	1.27E-09
	1.7	I02+ v2.1 - Mineral extraction - Midpoint [MJ surplus]	0.00450066	0	0	0	0.0045007	0	0
1.8	Energy								
		Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ	284.4175469	284.417547	0	0	0	0	0
		Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	256.4630721	256.463072	0	0	0	0	0
		Primary energy from resources (gross cal. value) [MJ]	284.4175469	284.417547	0	0	0	0	0
		Primary energy from resources (net cal. value) [MJ]	256.4630721	256.463072	0	0	0	0	0
1.9	TRACI								
	1.9.1	TRACI, Eutrophication [kg N-Equiv.]	0	0	0	3.68602654	0	0	3.686026539
	1.9.2	TRACI, Global Warming Air [kg CO2-Equiv.]	0	0	0	16.0901158	0	0	16.09011585
	1.10	UBP, Ecological scarcity method [UBP]	256.4630721	256.463072	0	438169.155	0	0	438169.1548

2		Technical quantities							
2.1	VDA material classification: Steel and iron materials								
	2.1.1	Steels / cast steel / sintered steel (unspecified) [kg]	0.000196214	0	0	0	0.000196	0	0
2.2	Materials and material compounds [kg]		0.025350653	0	0	0	0	0	0.025350653
2.3	Fuels and auxiliary means [kg]		416.67	416.67	416.67	0	0	416.67	0
2.4	Energy								
		Energy (gross calorific value) [MJ]	415.5684912	288.3675753	127.20092	792.035703	0	289.962088	369.4626601
		Energy (net calorific value) [MJ]	665.6160179	857.4673993	285.20205	792.035703	70.0405	567.964089	369.4626601
		Energy ren. (gross calorific value) [MJ]	0	0	0	0	0	289.962088	369.4626601
		Energy ren. (net calorific value) [MJ]	0	0	0	0	0	289.962088	369.4626601
		Energy renewable and non renewable (gross calorific value) [MJ]	284.4175516	284.4175516	0	0	0	289.962088	369.4626601
		Energy renewable and non renewable (net calorific value) [MJ]	256.4630667	256.4630667	0	0	70.0405	289.962088	369.4626601
2.5	Mass [kg]		422.5457748	422.5192154	416.67019	422.513399	0.000491	416.670167	422.5383974
2.5	Standard volume [Nm3]		7.290888156	7.290888156	0	0	0	0	0
2.6	Volume [m3]		1.07E-05	0	0	0	0	0	1.07E-05

Appendix F GaBi OUTPUT Results

		Quantities		Combustion Chamber	Compressor	Gas Turbine	Generator	Solar Receiver	Thermal storage
1.		Environmental quantities							
1.1	EDIP 1997, Resource quantities								
	1.1.1	EDIP 1997, Copper [kg]	0.000122634	0	0	0	0.0001226	0	0
1.2	CML2001								
	1.2.1	CML2001 - Dec. 07, Abiotic Depletion (ADP) [kg Sb-Equiv.]	2.38201E-07	0	0	0	2.382E-07	0	0
	1.2.4	CML2001 - Nov. 09, Abiotic Depletion (ADP elements) [kg Sb-Equiv.]	1.67508E-07	0	0	0	1.675E-07	0	0
	1.2.7	CML2001, Abiotic Depletion (ADP) [kg Sb-Equiv.]	0.241627518	0.38096917	0.00308804	0.06442	0.0010103	0	0.1731083
	1.2.8	CML2001, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	135.829618	135.829618	0	135.83	0	0	135.82962
	1.2.9	CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	16.09011585	16.0901158	0	16.0901	0	0	16.090116
1	CML96								
	1.3.1	CML96, Eutrification potential (EP) [kg Phosphate-Equiv.]	1.621851677	1.62185168	0	1.62185	0	0	1.6218517
	1.3.3	CML96, Global warming potential (GWP 20 years) [kg CO2-Equiv.]	16.09011585	16.0901158	0	16.0901	0	0	16.090116
	1.3.4	CML96, Global warming potential (GWP 500 years) [kg CO2-Equiv.]	16.09011585	16.0901158	0	16.0901	0	0	16.090116
1	EDIP 1997								
	1.4.1	EDIP 1997, Ecotoxicity soil chronic [m3 soil]	0.09132028	0	0	0	0.0913203	0	0
	1.4.2	EDIP 1997, Ecotoxicity water chronic [m3 water]	3.433756683	0	0	0	3.4337567	0	0
	1.4.4	EDIP 1997, Human toxicity air [m3 air]	6370.606091	0	0	0	6370.6061	0	0
	1.4.5	EDIP 1997, Human toxicity soil [m3 soil]	0.132359507	0	0	0	0.1323595	0	0
	1.4.6	EDIP 1997, Human toxicity water [m3 water]	0.001654446	0	0	0	0.0016544	0	0
2	EI95								
	1.6.1	EI95, Heavy metals [kg Pb-Equiv.]	0.000891521	0.00017325	0.00019013	0.00036	0	0.00017	4.65E-06
2	EI99								
	1.7.3	EI99, EA, Human health, Climate Change [DALY]	3.37892E-06	3.3789E-06	0	3.4E-06	0	0	3.379E-06
	1.7.4	EI99, EA, Resources, Minerals [MJ surplus energy]	0.00450066	0	0	0	0.0045007	0	0
	1.7.5	EI99, HA, Ecosystem quality, Ecotoxicity [PDF*m2*a]	0.231795384	0.0450447	0.04943364	0.09271	0	0.0434	0.0012089
	1.7.6	EI99, HA, Human health, Carcinogenic effects [DALY]	4.63591E-06	9.0089E-07	9.8867E-07	1.9E-06	0	8.7E-07	2.418E-08
	1.7.9	EI99, IA, Ecosystem quality, Ecotoxicity [PDF*m2*a]	0.030311704	0.00589046	0.0064644	0.01212	0	0.00567	0.0001581
	1.7.10	EI99, IA, Human health, Carcinogenic effects [DALY]	1.96135E-07	3.8115E-08	4.1828E-08	7.8E-08	0	3.7E-08	1.023E-09
	1.7.11	EI99, IA, Human health, Climate Change [DALY]	3.21802E-06	3.218E-06	0	3.2E-06	0	0	3.218E-06
2	IO2+ v2.1								
	1.8.4	I02+ v2.1 - Mineral extraction - Midpoint [MJ surplus]	0.00450066	0	0	0	0.0045007	0	0
2	TRACI								
	1.9.1	TRACI, Eutrophication [kg N-Equiv.]	3.686026539	3.68602654	0	3.68603	0	0	3.6860265
	1.9.2	TRACI, Global Warming Air [kg CO2-Equiv.]	16.09011585	16.0901158	0	16.0901	0	0	16.090116
1.1(	UBP, Ecological scarcity method [UBP]		438169.1548	438169.155	0	438169	0	0	438169.15

2		**Technical quantities**							
2.1	VDA material classification: Steel and iron materials								
	2.1.1	Steels / cast steel / sintered steel (unspecified) [kg]	0.000196214	0	0	0	0.0001962	0	0
2.2	Materials and material compounds (unspecified) [kg]		0.025350653	0	0	0	0	0	0.0253507
2.3	Fuels and auxiliary means (unspecified) [kg]		0	0	416.673	0	0	416.67	0
2.4	Energy								
	2.4.1	Energy (gross calorific value) [MJ]	584.1842061	792.035703	296.382134	503.394	70.040504	13.9001	359.89259
	2.4.2	Energy (net calorific value) [MJ]	584.1842061	792.035703	296.382134	731.435	70.040504	610.954	359.89259
	2.4.3	Energy ren. (gross calorific value) [MJ]	81.84058925	0	289.962088	369.463	67.940489	13.9001	0
	2.4.4	Energy ren. (net calorific value) [MJ]	81.84058925	0	289.962088	369.463	67.940489	13.9001	0
	2.4.5	Energy renewable and non renewable (gross calorific value) [MJ]	81.84058925	0	289.962088	369.463	67.940489	13.9001	0
	2.4.6	Energy renewable and non renewable (net calorific value) [MJ]	81.84058925	0	289.962088	439.503	67.940489	13.9001	0
2.5	Mass [kg]		422.5397748	422.513215	416.67319	422.513	0.0004905	416.67	422.5384
2.6	Volume [m3]		1.07191E-05	0	0	0	1.072E-05	0	1.072E-05

Appendix G Balanced input/output RESULTS in GaBi

	Brayton Cycle	Combustion Chamber	Compressor	Gas Turbine	Generator	Solar Receiver	Thermal storage
Environmental quantities							
CML2001 - Dec. 07, Abiotic Depletion (ADP) [kg Sb-Equiv.]	0.12335981	0.123359813	0	0	0	0	0
CML2001 - Dec. 07, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	135.829618	135.829618	0	0	0	0	0
CML2001 - Dec. 07, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
CML2001 - Dec. 07, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	-0.000731	-0.000142064	-0.000155906	-0.000292397	0	-0.000136867	-3.81E-06
CML2001 - Nov. 09, Abiotic Depletion (ADP fossil) [MJ]	256.463072	256.4630721	0	0	0	0	0
CML2001 - Nov. 09, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	135.829618	135.829618	0	0	0	0	0
CML2001 - Nov. 09, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
CML2001 - Nov. 09, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	-0.000731	-0.000142064	-0.000155906	-0.000292397	0	-0.000136867	-3.81E-06
CML2001, Abiotic Depletion (ADP) [kg Sb-Equiv.]	-0.0551839	-0.255709396	0.058095598	0.316548379	-0.001010107	0	-0.173108336
CML2001, Eutrophication Potential (EP) [kg Phosphate-Equiv.]	135.829618	135.829618	0	0	0	0	0
CML2001, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
CML2001, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	-0.000731	-0.000142064	-0.000155906	-0.000292397	0	-0.000136867	-3.81E-06
CML96, Eutrification potential (EP) [kg Phosphate-Equiv.]	1.62185168	1.621851677	0	0	0	0	0
CML96, Global warming potential (GWP 100 years) [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
CML96, Global warming potential (GWP 20 years) [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
CML96, Global warming potential (GWP 500 years) [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
EDIP 1997, Global warming potential (GWP 100 years) [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
EDIP 2003, Global warming [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
EI95, Heavy metals [kg Pb-Equiv.]	0.00089152	0.000173249	0.000190129	0.000356582	0	0.000166911	4.65E-06
EI99, EA, Ecosystem quality, Ecotoxicity [PDF*m2*a]	0.23179538	0.045044705	0.049433636	0.092711208	0	0.043396912	0.001208923
EI99, EA, Human health, Carcinogenic effects [DALY]	4.64E-06	9.01E-07	9.89E-07	1.85E-06	0	8.68E-07	2.42E-08
EI99, EA, Human health, Climate Change [DALY]	3.38E-06	3.38E-06	0	0	0	0	0
EI99, EA, Human health, Respiratory (inorganic) [DALY]	-3.34E-07	-6.50E-08	-7.13E-08	-1.34E-07	0	-6.26E-08	-1.74E-09
EI99, EA, Resources, Fossil fuels [MJ surplus energy]	22.8253464	22.82534644	0	0	0	0	0
EI99, HA, Ecosystem quality, Ecotoxicity [PDF*m2*a]	0.23179538	0.045044705	0.049433636	0.092711208	0	0.043396912	0.001208923
EI99, HA, Human health, Carcinogenic effects [DALY]	4.64E-06	9.01E-07	9.89E-07	1.85E-06	0	8.68E-07	2.42E-08
EI99, HA, Human health, Climate Change [DALY]	3.38E-06	3.38E-06	0	0	0	0	0
EI99, HA, Human health, Respiratory (inorganic) [DALY]	-3.34E-07	-6.50E-08	-7.13E-08	-1.34E-07	0	-6.26E-08	-1.74E-09
EI99, HA, Resources, Fossil fuels [MJ surplus energy]	38.4694608	38.46946081	0	0	0	0	0
EI99, IA, Ecosystem quality, Ecotoxicity [PDF*m2*a]	0.0303117	0.005890461	0.006464399	0.012123773	0	0.005674981	0.00015809
EI99, IA, Human health, Carcinogenic effects [DALY]	1.96E-07	3.81E-08	4.18E-08	7.84E-08	0	3.67E-08	1.02E-09
EI99, IA, Human health, Climate Change [DALY]	3.22E-06	3.22E-06	0	0	0	0	0
EI99, IA, Human health, Respiratory (inorganic) [DALY]	-2.44E-07	-4.75E-08	-5.21E-08	-9.77E-08	0	-4.57E-08	-1.27E-09
Primary energy demand from ren. and non ren. resources (gross cal. value) [MJ]	284.417547	284.4175469	0	0	0	0	0
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	256.463072	256.4630721	0	0	0	0	0
Primary energy from resources (gross cal. value) [MJ]	284.417547	284.4175469	0	0	0	0	0
Primary energy from resources (net cal. value) [MJ]	256.463072	256.4630721	0	0	0	0	0
TRACI, Eutrophication [kg N-Equiv.]	3.68602654	3.686026539	0	0	0	0	0
TRACI, Global Warming Air [kg CO2-Equiv.]	16.0901158	16.09011585	0	0	0	0	0
UBP, Ecological scarcity method [UBP]	438425.618	438425.6179	0	0	0	0	0