Life Cycle Assessment of a Solar Thermal Concentrating System

CHRISTOPHER J. KORONEOS, SOCRATES A. PIPERIDIS, CHRISTOS A. TATATZIKIDIS, DIMITRIOS C. ROVAS
Department of Engineering and Management of Energy Resources,
University of Western Macedonia,
Bakola & Sialvera, Kozani, 50100
GREECE

Abstract: - Solar energy could play a significant role in the replacement of fossil fuels leading to a clean energy solution with almost zero environmental impact. However, solar energy systems have some environmental impact. The objective of this work is the investigation of the environmental impacts of the solar energy utilization, in a solar thermal concentrating system for electricity production, with the employment of Life Cycle Assessment (LCA). This work is investigating the environmental impacts for the production of 1MW of electricity in a solar power tower plant. The work will take into consideration the input and output in all life cycle stages, from the raw material excavation till the end of life stage. The material use, the energy use and the emissions produced will be investigated. The construction period is taken to be 3 years while the life time of the solar power plant is 30 years.

Key-Words: - Solar Energy; Concentrated Solar Power; Solar Power tower; Life Cycle Assessment;

1 Introduction

The limited supply of fossil fuels and their environmental impacts have dictated the increasing usage of renewable energy sources. Although, there is an increase in the utilization of renewable energy sources there is still much to be done. To date, petroleum and natural gas remain the dominant energy sources, close to 65% of the consumed energy, while the renewable share is close to 7% [01]. Renewable electricity generation capacity reached an estimated 240GW worldwide in 2007, an increase of 50% over 2004, representing a 3.4% of global power generation [01]. Even though there is an annual increase of the solar energy utilization due to the photovoltaic grid connected systems, hydro power is the most “popular” renewable energy source for electricity generation. In future, concentrated solar power (CSP) is the most likely candidate for providing the majority of this renewable energy produced electricity. CSP technology is a proven technology for energy production, with a potential market increase, and significant cost reductions [02, 03].

Three main CPS technologies have been identified during the past decades for generating electricity

– Dish/engine technology, which can directly generate electricity,
– Parabolic trough technology producing high pressure superheated steam
– Solar tower technology.

1.1 Solar Dish/Engine Technology

A dish/engine system is a relatively small, standalone unit composed of a collector, a receiver, and an engine. A 250-kW plant is composed of ten 25-kW dish/engine systems and requires less than an acre of land [04]. Dish systems use dish-shaped parabolic mirrors as reflectors to concentrate and focus the sun's rays onto a receiver, which is mounted above the dish, at the dish focal center, where it absorbs the thermal energy and transfer it to the engine. The engine converts thermal energy to heat, and to mechanical power, by compressing the working fluid when it is cold, heating the compressed working fluid, and then expanding it through a turbine or with a piston that sets in motion an electric generator [04](fig. 1).

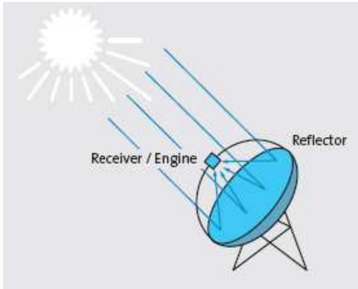

Fig. 1 – Dish Engine

In a dish/engine system, the working fluid can be heated up to 750 ^{o}C [05]. There is big potential for the receiver and the engine, including Stirling cycle, Brayton cycle, small gas turbine, micro turbines, and concentrating photovoltaic modules [03, 04, 05, 06]. Dish/engine systems use dual-axis collectors to track the sun [04, 07]. The ideal concentrator shape is parabolic, created either by a single reflective surface or multiple reflectors, or facets systems (stretched membrane or flat glass facets) [05]. Several dish/engine prototypes have successfully operated over the last years, ranging from 10 kW (Schlaich, Bergermann and Partner design), 25 kW (SAIC) to the 400 m^2 and 100 kW 'big dish' of the Australian National University [06], while within the European project EURODISH, a cost-effective 10 kW Dish Stirling engine for decentralized electric power generation has been developed by a European consortium. Currently dish/engine can generate about 25kw of electric power [04]. Because of their size, dish/engines are particularly well suited for remote, stand-alone power systems. Dish/engine's high optical efficiency and low startup losses make them the most efficient of all concentrated solar power technologies. It is estimated that there is a 29.4% efficient of solar to electricity conversion [06, 08]. Unfortunately, this technology is still in demonstration, due to its low reliability and the high capital cost of mass production. Current development and demonstration activities are aiming to the technical and economic issues should over runned before commercial prospects can be clarified.

1.2 Parabolic Trough Technology

A parabolic trough is a type of solar thermal energy collector. The collector field in the trough technology consists of a large field of single-axis tracking parabolic trough solar collectors [02]. Parabolic Trough systems, use parabolic trough-shaped mirrors to focus sunlight on thermally efficient receiver tubes (glass or mirror [12]), that run its length at the focal point and contain a heat transfer fluid (HTF) [10]. The HTF, usually oil, can be heated up to 390^{o}C [10]. Then, it circulates through a number of heat exchangers in order to produce superheated steam that drives a conventional thermodynamic cycle in order to produce electricity.

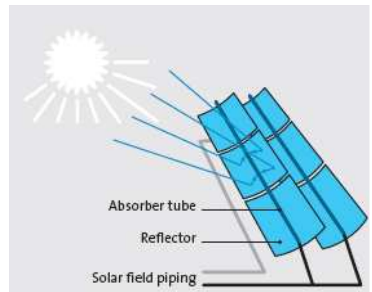

Fig. 2 – Parabolic Trough system

The spent steam is then condensed and pumped again through the heat exchangers to be superheated again, while the HTF is re-circulated through the solar field. The collectors have the potential to track the sun from east to west during the day, to ensure that the sun is continuously focused on the linear receiver tube [02]. Parabolic trough technology is currently the most proven of solar thermal technologies and the only one commercially available. In the USA there are nine large scale solar power plants operating since 1984 (SEGS I), in southern California [02,06]. The 30 MW plants near Kramer Junction, for example, each have about 10,000 modules with each module comprising 20 mirrors [09]. These systems range in size between 14 and 80MW [02, 06] producing daily 354MW of electricity at peak output [06]. SEGS gross production for 1985 to 2001 was 8305477MWh [02]. Besides USA, parabolic trough development is being pursued in Germany, Spain, Italy, Israel, and South Africa, and it is focused on the different HTF usage. Germany and Spain are developing a project that utilizes steam as a high-temperature working fluid in addition to oil, while Italy has a program (€100M) focused on troughs with a molten salt working fluid, to allow both higher temperatures and storage, based on the Solar II proven knowledge (Tower power technology).
Among CSP technologies, the efficiency of the trough technology is lower, due to the lower solar concentration and lower temperatures. It is estimated

that the parabolic trough technology efficiency is 20%. However, the great operating experience (over 20 years), the technology improvements and the cost reductions, made parabolic trough technology the least expensive and most reliable solar technology for near-term applications [06].

1.3 Solar Power Tower

Solar Power Tower (SPT) or central receiver systems use a circular field array of large individually sun tracking mirrors (hundreds to thousands), named heliostats, to focus sunlight onto a central receiver mounted on top of a tower [02, 03, 06]. By focusing the sunlight, 600-1000 times [03] temperatures from 800^oC to 1000^oC are achievable. The working fluid is circulated in the receiver in order to absorb the heat from the concentrated sunlight and then it is utilized in a thermodynamic cycle to produce electricity [03, 05, 06]. To date, SPT experiments have shown that the technology is technically feasible utilizing several working heat transfer mediums, such as steam, air and molten salts [03].

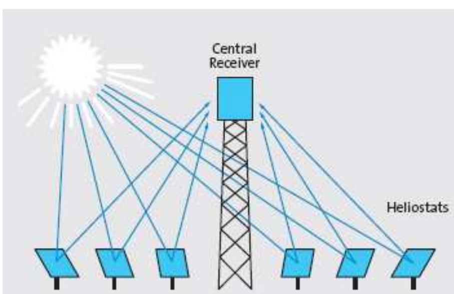

Fig. 3 – Solar Power Tower

The first demonstration power plants was Solar I, utilizing steam as a working medium, and Solar II, utilizing nitrate salt, (in Southern California), followed by the commercial implementation at Solar Tres project in Spain. In a typical installation, solar energy collection occurs at a rate that exceeds the maximum required energy to produce steam for the steam turbine. Consequently, a thermal storage system can be charged while the plant is producing power at full capacity. The Solar I thermal storage system, stored heat from solar-produced steam in a tank filled with rocks and sand using oil as the heat-transfer fluid, while Solar II used a tank to store heated nitrate salt. The hot salt stores enough energy to produce electricity for up to 3 hours during cloudy periods or after dark [05, 06, 10]. Current designs allow storage with sufficient capacity to power a turbine at full output for up to 13 hours [06]. The future potential of SPT plants is quite wishful. Studies have resulted that in the future, the potential to design large scale power plants producing from 30 to 200 MW of electric power, is achievable [05,10].

In Europe, Germany and Spain are focused on systems the use air as working medium. Initially the GAST project in the early 80s, shown a lack in the utilization of air, due to the overheating of the receiver tubes. Then the PHEOBUS project pulled air through a porous mesh (metal, ceramic) that was directly exposed to solar radiation (receiver). The generating temperatures are between 700 and 800^oC that can drive a 550^oC Rankine cycle. For higher temperatures, the mesh can be replaced by SiC and Al_2O_3 structures. This technique is tested at Platforma Solar in Almeria, where solar radiation is harvest by 350heliostats of 40m^2 area each. Additionally, an Israel project proposed to place a large hyperbolic secondary reflector on the top of a tower to beam the concentrated solar energy to ground level in order to achieve greater temperatures. This project successfully demonstrated achieved temperatures of 1200 ^oC.

The CSP systems are still immature and there are significant improvements need to be done in order to achieve reliability and effectiveness in their implementation. On the other hand, these technologies have reached a certain maturity, as has been demonstrated in pilot projects in Israel, Spain and the USA. The benefits from utilizing the CSP technology are not only environmental but also economic. Besides the fact that they reduce air pollutants and improve public health, they create new jobs in rural areas, reduce cash outflow for energy, increase capital investment and increase GSP [11].

1.4 Environmental Sustainability

Life cycle assessment of the concentrating solar power systems shows that they are best suited for the reduction of greenhouse gases and other pollutants, without creating other environmental risks or contamination [12]. For example, each square meter of collector surface can avoid 250-400 kg of CO_2-emissions per year (fig. 4). This life cycle assessment of CO_2-emissions is based on the present energy mix of Germany. CSP value is valid for an 80 MW parabolic trough steam cycle in solar only operation mode. PV and CSP in North Africa. CC: Combined Cycle. Source: DLR.

The energy payback time of the concentrating solar power systems is in the order of only 5 months. This compares very favorably with their life span of approximately 25- 30 years. Most of the collector materials can be recycled and used again for further plants.

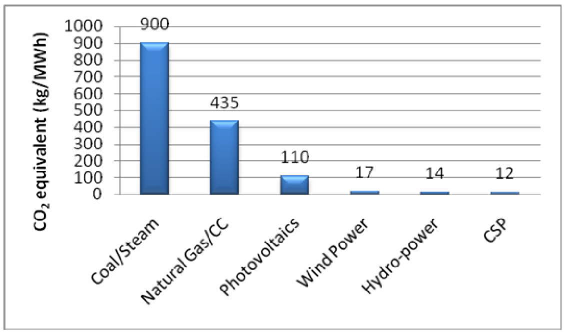

Figure 4. Life Cycle CO_2-Emissions of Different Power Technologies

2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a useful tool to asses the environmental impact of a product, process or service and together can be very useful to the comparison of similar products. Life Cycle Assessment can be very helpful to engineers and researchers. The application of the LCA methodology, can lead to techniques that minimize the magnitude of pollution, conserve fuels and ecological systems, develop and utilize cleaner technologies and maximize recycling Although LCA is a relatively new method it has been accepted by industries worldwide. LCA methodology is applied in the products eco-design, development of new techniques to improve products, as the global trend is towards to the environmental issues. The Life Cycle assessment can be used in all sorts of industries.

Environmental life cycle assessment is a method for the analysis of environmental effects of economic products. It covers a wide range of environmental themes and takes the total production chain 'from cradle to grave' into account. Life Cycle Assessment is to provide a holistic picture of the environmental impacts of a given system, while being relevant both at a global scale, i.e., for global impact categories such as climate change, and at a smaller scale, i.e., for regional impact categories. Among those, the LCA approach, which considers the whole product life cycle, is recommended by the European Union and UNEP. The EU communication on Integrated Product Policy states that "All products cause environmental degradation in some way, whether from their manufacturing, use or disposal. Integrated Product Policy (IPP) seeks to minimise these impacts by looking at all phases of a product's life cycle and taking action where it is most effective" [13].

The stages of Solar Tower Power Plant's LCA from construction to recycling of its parts are the ones presented below:

- Raw materials excavation
- Materials processing
- Construction of the parts of Solar Power Tower Plant
- Transportation and assembly of the parts
- Operation of the Solar Tower Power Plant
- Decommissioning-Recycling
- Products disposal

The main operation of the system of Solar Power Tower is the exploitation of solar radiation and its conversion, firstly in thermal and continuously to electrical energy. In all the life cycle stages there are inputs and outputs. The inputs are energy, water and materials, while in outputs there are air and liquid emissions, solid wastes and the product, in this case electric power. In the operational stage the energy input is direct solar radiation that prostrates systems' sun-tracking mirrors. The functional unit of the analysis is set to be 1MWel and the operational life of the system is 30 years. The construction period is 3 years.

ISSN: 1790-2769

ISBN: 978-960-474-009-3

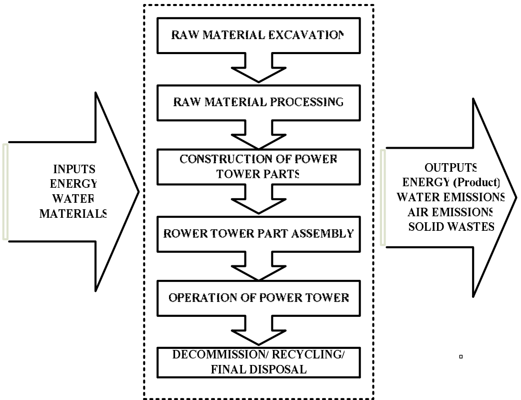

Fig. 5 – Life Cycle Stages

In the analysis done, there are several assumptions made. For instance, during the operation period no replacement of any element of the Solar Tower Power Plant is taking place (fig. 1). Additionally, no hazardous gaseous or liquid emissions are released during operation of the solar power tower plant. In present study plant under study, there is no heat storage, thus no salt usage. In the case where there was heat storage no additional emissions occur; if a salt spill occurs, the salt will freeze before significant contamination of the soil occurs. Salt is picked up with a shovel and can be recycled if necessary [05].

The Solar Tower Power Plant has a nominal capacity of 1 MW and covers land and area of $4.07x10^6$ m^2, of which 7000 m^2 [14] is the area covered by the heliostats.

The required materials for the construction of the plant are listed in table 1and fig. 6[14].

Table 1 – Construction Materials

Materials	Tns
Aluminum (0.29%)	32
Concrete (16.9%)	1850
Copper (64.34%)	7050
Chromium (12.5%)	1375
Glass (0.62%)	68
Plastic (0.1%)	11.5
Steel (5%)	545
Insulation (0.25%)	27.5
Total	10959

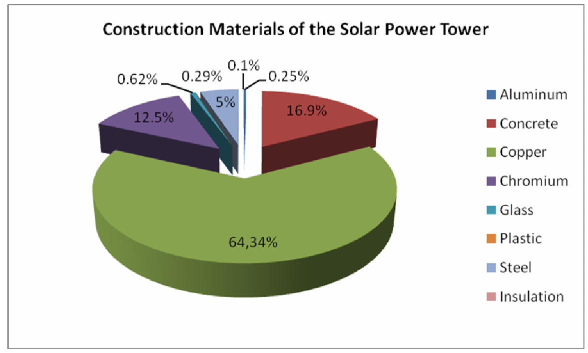

Fig. 6 – Construction Materials of the Solar Power Tower system

The energy used in the production of 1 ton of each material and its distribution is presented in Table 2 [14]. It is assumed that the materials are being transported from a region 100Km far from the plants' location with 200, 40tns diesel trucks [12]. The diesel usage and the emissions from the trucks for 1tKm distance are presented in table

Table 2 – Energy usage for material production

	Coal (MJ/tone)
Aluminum	1980
Concrete	360
Copper	13914
Chromium	51480
Glass	-
Plastic	7596
Steel	33840
Insulation	5464.14
	Crude Oil (MJ/tone)
Aluminum	1.84884
Concrete	0.266676
Copper	27.9456
Chromium	66.456
Glass	67.6
Plastic	45.582
Steel	23.3874
Insulation	39930
	Natural Gas (MJ/tone)
Aluminum	9205
Concrete	633.145

Copper	20265
Chromium	42700
Glass	154.4
Plastic	2660
Steel	11760
Insulation	72480
Total	
Aluminum	11186.84884
Concrete	993.411676
Copper	34206.9456
Chromium	94246.456
Glass	222
Plastic	10301.582
Steel	45623.3874
Insulation	117874.14

Table 3 – Diesel oil use and emissions of a 40ton truck

Truck 40 tones			
Input	**Output**		**Distance**
Diesel fuel: 0.348 Kg	**CH4**	.0000197 K	**1 tKm**
	CO	0.00114 Kg	
	CO2	1.1 Kg	
	NOx	0.00992 Kg	
	SO2	).000209 Kg	

It is observed that the 1 ton of insulation has the highest energy requirements for its production (Table 2). On the other hand insulation has a small share of the construction materials. The total energy consumption for the production of the total amount of materials used in the plant is presented in Table 4 and fig. 7. Figure 8 presents the share of the coal, crude oil and natural gas. The diesel oil contribution to the development of the power plant is minimum compare to other fossils.

Table 4 – Total energy use for the material production of the Power Plant

	MJ/Plant
Aluminum (0.09%)	357979.1629
Concrete (0.46%)	1837811.601
Copper (60.11%)	241158966.5
Chromium (32.3%)	129588877
Glass (0.004%)	15096
Plastic (0.03%)	118468.193
Steel (6.2%)	24864746.13
Insulation (0.8%)	3241538.85
Total	**401183483.4**

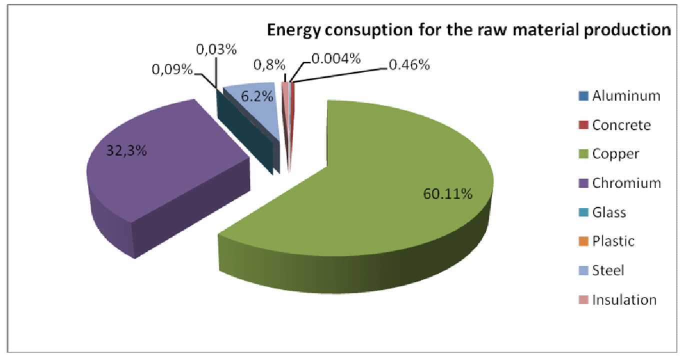

Figure 7 – Total energy use for the material production of the Power Plant

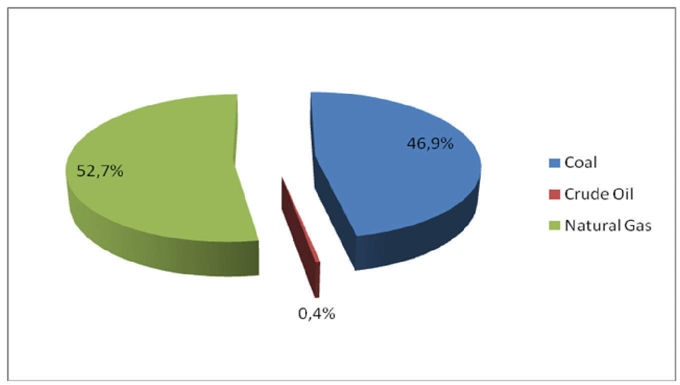

Fig. 8 - Total Energy Distribution

Utilizing the Gabi data base, the air and water and the solid waste have been gathered [15]:

3. Impact Assessment

3.1 Impact Categories Selection and Determination

In the present study are assessed the impacts that contribute to the following:

- Greenhouse Effect
- Stratospheric Ozone Depletion

- Acidification
- Eutrophication
- Carcinogenesis
- Winter Smog
- Summer Smog
- Heavy Metals

Classification

In the classification process emissions are associated with impacts categories. In this study emissions are proportioned to all impacts categories. Emissions are considered that they contribute 100% to all impacts categories.

Characterization

In the characterization process emissions are quantified. Each emission is converted to equivalent units for each impact using Eco-Indicator's characterization factor. The equivalent quantities for every impact category are presented in table 5

Table 5 – Equivalent Quantities of Impact Categories

	Equivalent Quantities (Kg)
Greenhouse Effect (CO_2)	6.82E+06
Acidification (SO_2)	8.51E+03
Eutrophication(air) (PO_4)	1.42E+03
Eutrophication(water) (PO_4)	1.154034552
Stratospheric Ozone Depletion (CFC-11)	2.57E-02
Carcinogenesis (B(a)P)	4.82E-02
Winter Smog (SPM)	8.43E+02
Summer Smog (C_2H_4)	1.82E+01
Solid Waste	1.07E+02
Heavy Metals(air) (Pb)	5.76E-01

Normalization

Normalization follows characterization, and is the process which associates each impact with the region

The normalization Values of the analysis are

Table 6- Normalization Values of the Analysis

	Normalization Values
Greenhouse Effect	5.06E+02
Acidification	7.55E+01
Eutrophication(air)	3.73E+01
Eutrophication(water)	3.02E-02
Stratospheric Ozone Depletion	3.18E-02
Carcinogenesis	5.11E+00
Winter Smog	8.94E+00
Summer Smog	9.25E-01
Solid Waste	0.00E+00
Heavy Metals(air)	1.02E+01
Heavy Metals(water)	1.89E+00

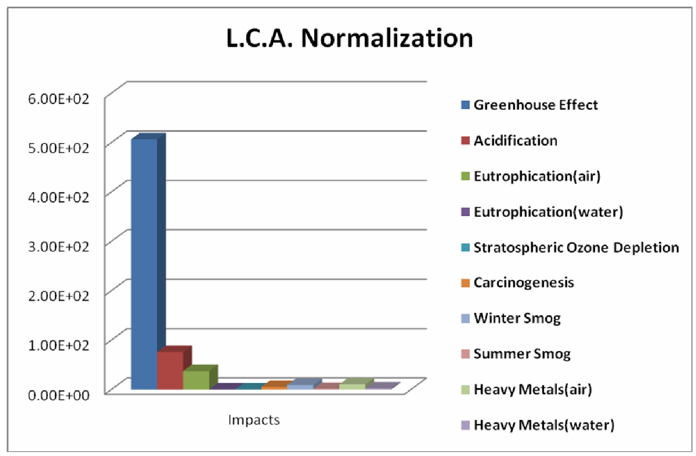

Fig. 9 – Normalization Diagramm

Evaluation

Evaluation is the final step of this L.C.A. study, where all impacts are associated between them and the significance of each impact category is assessed

Table 7 – Evaluation Values of the Analysis

	Impact Valuation Values
Greenhouse Effect	1.27E+03
Acidification	7.55E+02

Eutrophication(air)	1.86E+02
Eutrophication(water)	1.51E-01
Stratospheric Ozone Depletion	3.18E+00
Carcinogenesis	5.11E+01
Winter Smog	4.47E+01
Summer Smog	2.31E+00
Solid Waste	0.00E+00
Heavy Metals(air)	5.12E+01
Heavy Metals(water)	9.46E+00

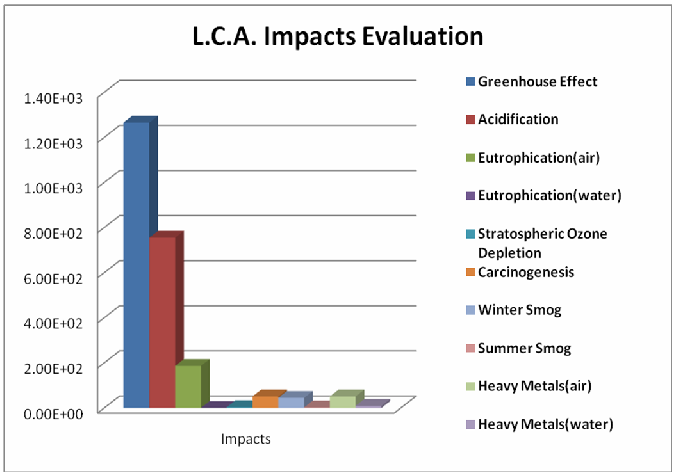

Fig. 10 – Evalution Diagramm

Conclusions

The dominant impact category in the construction and operation of a Power Tower plant is the Greenhouse effect, followed by the acidification and air eutrophication. The dominant air emission that affects the GH effect is CO_2, while in Acidification is the NO_x [14]. Thus, in order to design a more sustainable and environmental friendly power plant, there must be interfering in that life cycle process that has the maximum contribution to the generation of these emissions.

Copper and Chromium are the dominant materials used in the construction of the power tower plant. Additionally, the coal consumption represents the 46,9% of the overall energy consumption. The 54,6% of the energy used in the chromium production came from the coal combustion, while the total amount of copper required for the power plant requires the highest consumption of energy and almost 40% of it came from coal combustion. Among the utilized solids fuels in the production of the materials coal produces the majority of CO_2 and NO_x emissions.

According the above coal usage minimization is the first and achievable in short terms, step in the minimization of the environmental impact. The energy gap that will rise from the coal minimization can easily be replaced by natural gas. Natural gas, compare to coal has significant less CO_2 and NO_x emissions. Another route is the usage of Nuclear power, although from the perspective of LCA it is not a sustainable solution, if we consider the nuclear waste production and their final disposal impact. Last but not least renewable energy can be utilized in the production of these materials, renewable for renewable. This is the best scenario, although it is not directly implemented.

Another route is the further treatment of flue gasses before their emission to the atmosphere. Carbon sequestration and NO_x capture can contribute in this.

Compare to other electricity production methods, GSP plants are the most sustainable of all, taking into consideration their whole life cycle (fig. 4). On the other hand they can be further "evolved". Besides the research in the field of operational stage, there must be a research in the material usage. The minimization or replacement of copper for instance, with another less pollutant material, will develop a power plant with the minimum environmental impact.

References

[1] http://www.eia.doe.gov/cneaf/solar.renewables/page/rea_data/rea_sum.html

[2] Subcontractor report, *" Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts",* October 2003, NREL/SR-550-34440

[3] Hans Muller – Steinhagen, Franz Trieb, "*Concentrating solar power - A review of the*

technology", Quarterly of the Royal Academy of Engineering Ingenia 18, February/March 2004

[4] Energy Efficiency and Renewable Energy, *"Concentrating Solar Power: Energy from Mirrors"* DOE/GO-102001-1147 FS 128, March 2001

[5] EPRI Project Manager, E.A. DeMeo, *"Renewable Energy Technology Characterizations"*, TR-109496, Final Report, December 1997

[6] Status Report on Solar Thermal Power Plants, Pilkington Solar International: 1996. Report ISBN 3-9804901-0-6.

[7] SOLAR DISH ENGINE (www.solarpaces.org)

[8] Washom, B., "*Parabolic Dish Stirling Module Development and Test Results",* Paper No. 849516, Proceedings of the IECEC, San Francisco, CA (1984).

[9] Parabolic Trough Solar Collector Systems Made More Energy Efficient, http://www.sciencedaily.com/releases/2007/05/070515174832.htm]

[10] Concentrating Solar Power Program, Office of Solar Energy Technologies Power Towers, *"Proving the technical feasibility and cost potential of generating large-scale electric power from the sun when it is needed, day or night",* National Renewable Energy Laboratory a DOE national laboratory, DOE/GO-10098-468, September 1998, revised August 2000

[11] Scott Jones, *"Concentrating Solar Power: The 'Other'Solar…A Systems Perspective",* Sandia National Laboratories, October 19, 2004

[12] Concentrating Solar Power Now, Deutsches Zentrum für Luft und Raumfahrt e.V., German Aerospace Center,.

[13] http://www.unep.org/

[14] U.S. Department of Energy, *"Energy Technology Characterizations Handbook, Environmental Polution and Control Factors",* March 1983, Third Edition,DOE/EP – 0093, Dist. Categoory UC - 11

[15] Gabi Data Base

[16] Exploiting the heat the sun to combat climate change, Concentrated Solar Thermal Power – Now!, By Greenpeace, ESTIA, SolarPACES, September 2005www.greenpeace.org/raw/content/international/press/reports/**Concentrated-Solar Thermal-Power**.pdf

[17] SOLAR PARABOLIC TROUGH (www.solarpaces.org)

[18] B.J. Groenendaal, *"Solar Thermal Power Technologies, Monograph in the framework of the VLEEM Project"*, July 2002 ECN-C--02-062

[19] F. Trieb, J. Nitsch, S. Kronshage, C. Schillings, L.A. Brischke, G. Knies, G. Czisch, *"Combined Solar Power and Desalination Plants for the Mediterranean Region, Sustainable Energy Supply using Large Scale Solar Thermal Power Plants",* Solar Power and Desalination for the Mediterranean Region, EUROMED 2002, Sinai, Egypt, May 4-7, 2002,

[20] Scott Elrod , *"Solar Concentrators*", Palo Alto Research Center, 3333 Coyote Hill Road Palo Alto, CA 94304, elrod@parc.com

[21] SOLAR POWER TOWER (www.solarpaces.org)

[22] European Commission, Concentrating Solar Power, From Research to Implementation, Directorate - General for Energy and Transport, Directorate - General for Research (www.solarpaces.org)

[23] MASSACHUSETTS INSTITUTE OF TECHNOLOGY, Department of Civil and Environmental Engineering, 1.020 Ecology II: Engineering for Sustainability, Problem Set 6 – Life Cycle Analysis, Transport, Economics.