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Environmental assessment of small scale solar thermal electricity generation

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Abstract. Solar thermal electricity probably has the greatest potential of any single renewable energy process and it can be economically competitive with other technologies, if environmental costs are accounted for. In spite of the many investigations conducted so far there is no one dominant technology and no single life cycle assessment study conducted to compare different STE technologies. This life cycle study has been undertaken to identify potential materials flow, energy consumption and emissions for small scale STE options. The processes are described by the typical process inputs and outputs including energy, materials, solid wastes and other emissions. The results show sufficient efficiency for Australian conditions of small scale.

1. Introduction

Solar thermal electricity (STE) may be defined as the process by which collected solar energy is converted to electricity through the use of some kind of heat-to-electricity conversion device. STE probably has the greatest potential of any single renewable energy process and it can be economically competitive with coal-generated electricity if environmental costs are accounted for [1]. STE on grid was not achieved until the 1980s, although the basic technology for the production of mechanical energy had been under development for more than hundred years. During the last two decades, there has been rapid development in the basic technology, and prospects for rapid growth now appear to be very bright for newer approaches studied by a number of research groups [2-4]. In addition, approaches such as combined cycle power generation are being advanced by many to improve the overall energy conversion efficiency [4]. The world potential market places for STE technologies presented in Figure 1.

However, although many investigations have been conducted so far and some STE power plants are working more than two decades, unlike solar PV system, there is no one dominant technology for solar thermal power generation. And up to now there is no a single life cycle assessment (LCA) study conducted to compare different STE generation technologies, although some studies have been done to estimate current and future projection of costs based on accumulated experience [3]. Obviously, such analysis should be done before the large-scale implementation of STE technologies.

Taken into account the above mentioned situation, the whole LCA study has been divided in two parts: 1) design of most appropriate STE system in terms of its overall efficiency, cost effectiveness and environmental impact based on published in the literature results [6, 7] and 2) estimation of

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potential environmental impact of the adopted system in the frame work of LCA methodology. To estimate environmental impact of the adopted STE the whole life cycle approach is adopted, viz. production and assembly of components, operation and disassembly and recycling. By chaining all processes, the assessment of the total impact on the environment and on energy and material resources demand can be done over the whole life cycle of the STE system.

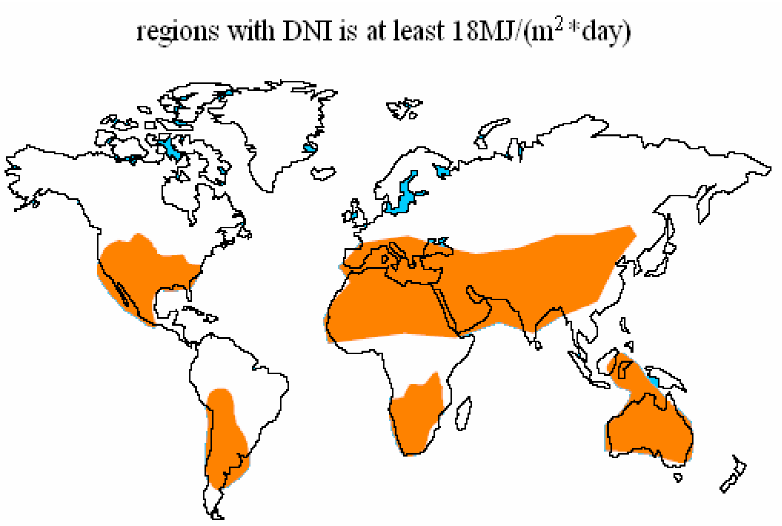

Figure 1. Potential solar thermal power marketplace [5].

2. Design of a small-scale STE system

There are three major types of concentrators: power tower, dish, and parabolic trough. The latter is most suitable for STE systems, as it is most efficient for medium temperature collectors (150–400°C). A north-south tracking axis orientation gives a high summer bias to annual electricity output, which is useful in Australia. Recently, considerable work has been undertaken to reduce structural cost, so it becomes the least expensive and most reliable solar concentrator technology. The performance of such concentrator can reach about 92% (the amount of absorbed solar radiation energy).

The major components of the system (shown in Figure 2) are briefly described below.

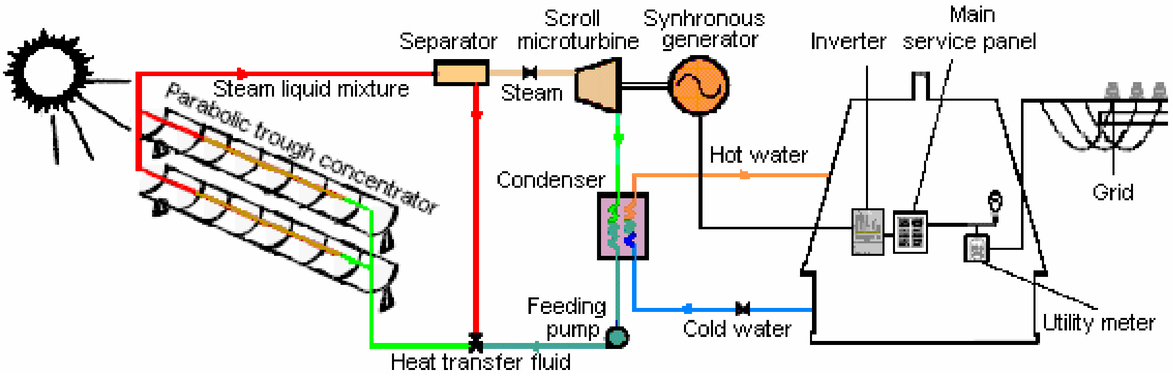

Figure 2. Schematic of the proposed solar thermal electricity generation system.

Solar collector: Two parabolic troughs working in parallel driven by tracking device govern by control unit.

Receiver and Heat Transfer Fluid: The main feature of the receiver is to covert the energy of solar radiation to heat energy using a heat transfer fluid (HTF), which transfers the absorbed energy further down to a device converting heat to mechanical energy. The absorbed solar radiation heats and vaporises HTF. A mixture of water and ammonia is adopted with the Kalina cycle [8]. The receiver employed for this system is based on works [9]. Steam created in the receiver is separated from the liquid in the separator. A T-junction separator is used [10]. Separated steam is then directed to micro-scroll turbine [11], where heat energy of the steam is converted to mechanical energy.

The steam from turbine is converted to liquid inside the heat exchanger. The heat from the steam recovered by cooling water inside heat exchanger can be used for household needs.

The feed pump is pumping working fluid (water-ammonia mixture) back to the receiver to close thermodynamic cycle.

The synchronous generator seating on the scroll micro-turbine shaft generates DC. The DC is converting to AC with voltage of 240V, which can be consumed on the spot or supplied to the grid.

To be workable, the STE system needs other balance-of- system (BOS) components. In material and energy analysis of STE system the BOS cannot be neglected as they represent rather significant part of overall system. Some complementary devices, which must be added to the proposing STE system, are: steam separator, heat exchanger, pump, inverter and sun tracking device.

A connection to the grid of small STE could be made at the node where voltage doesn't exceed 400V, i.e. it should be very close to consumers. Figure 3 shows a generalised scheme of the combined electric power system, which includes renewable energy sources.

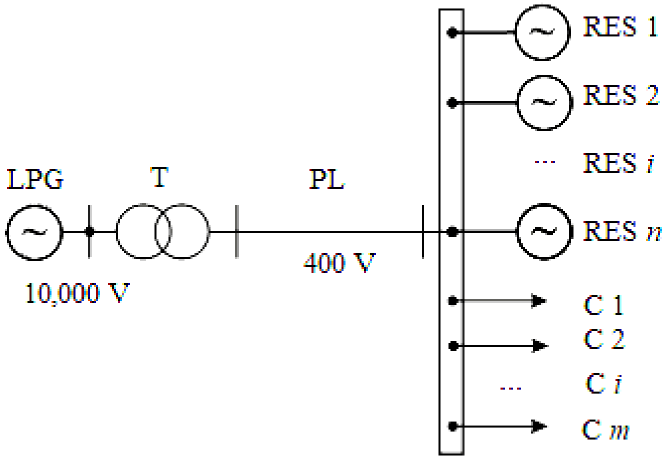

Figure 3. Generalised scheme of the combined electric power system.
LPG is a local power grid;
T is a step-down transformer: 10000/400V;
PL is a power line;
RES_1-RES_n are sources of renewable energy;
C_1-C*m* are consumers

During use of such system the reverse generation modes may occur. Under such mode, the electrical energy from renewable energy sources (RESs) goes to electrical grid. Such mode is a positive situation for companies using "green tariffs" However, in the case of commensurate of the power of the transformer and RESs, the latter substantially influence working parameters of PL, which may exceed allowed voltage deviation [12]. Figure 3 presents simplified scheme for the reverse generation regime at the points of the joints of the consumers. If the transverse component of the voltage drop and power within power lines are not taken into account, then voltages at those points could be found by expression:

$$U = U_1 - \Delta U_{\mathrm{PL}} = U_1 - \frac{-P}{U_{\mathrm{NOM}}^2} r_{\mathrm{PL}},, \tag{1}$$

where, U is voltage at the points of SREs joints; U_1 is voltage at the beginning of PL; ΔU_{PL} is magnitude of voltage drop within PL (for the reverse generation mode ΔU_{PL} must be subtracted from U); P is power generated by SREs to the grid; U_{NOM} is nominal mode voltage; r_{PL} is active resistance of PL.

Expression (1) shows that increasing power generation by RESs increases PL voltage U at the points of joints of the consumers. Therefore, the mode of increasing RESs power generation may overcome allowed voltage deviation of PL at the points of joints of the consumers. Such extremal voltage deviation adversely effects reliability of electrical devices of the consumers, leads to reduction their service lives, and, as a consequence, to substantial economic loses [13].

Currently, there are several ways to solve this problem, the main of which are following: 1) measures to increase capacity of electricity distribution by grid elements; 2) measures to limit energy generation by RESs.

The first way requires reconstruction of the grid (replacing transformers with more powerful ones, replacing cables with those with bigger cross-section, etc.) Such approach requires significant capital investment by owners of RESs and as a consequence increase payback period of RESs and decrease their economic efficiency. The second way leads, on the one hand, to under receiving of money due to sale electricity by “green tariffs”, although, on the other hand, it reduces economic losses due to extreme values of voltage deviation in the grid.

The most promising approach seems to be automatic control of power generated by RESs. Thus, the maximum level of power generation within the grid would be determined jointly by the profit from sale of electricity by “green tariffs” and reduction of economic losses from excessive voltage deviations. The implementation of such approach is possible through improvement of automatic control system (ACS) of power generation by RESs [14].

3 Life cycle assessment: goal, scope, and major assumptions

3.1 Purpose, scope and functional unit

The purpose of the LCA study is to investigate the environmental impact from the whole life cycle of the above STE generation system. A consequence of this objective is that the production level of the order of 100,000 STE units with capacity 3-5kW will be required to contribute 5% to current electricity supply (these figures are based on Australia electricity for the year 2017 [15]).

The scope of material flow analysis for the LCA study includes direct and indirect material inputs. The scope for the energy requirements, however, is broader and covers also the energy use for the production of materials and for the production of capital equipment for main materials.

The functional unit is assumed as the STE system itself, i.e. a system that produces an average of 3kW electrical energy from solar radiation. The overall efficiency of the STE system is 20%.

Hot water production (from the heat rejected within thermodynamic cycle) is not taken into account as it requires additional assumptions regarding its usage. The boundary of LCA study of the STE system is presented in Figure 4.

3.2 Major assumptions

The proposed STE system with overall efficiency 20% has been adopted from a detailed study of efficiencies of the main parts of the system.

The life cycle of each part of the STE system starts from the production of necessary materials (beginning from mining of natural resources) and then fabricating the different parts of the system (data for materials production and parts fabrication have been taken from SimaPro database [16] adopted for Australian conditions with taken into account all necessary transportations). Finally, the system is assembled and tested. At the use stage, the module produces electrical energy during 20 years (the lifetime of the system was assumed according [16]). At the end of the lifetime of the system, it will be decommissioned and the resulting waste will have to be disposed in a responsible way. As this event can occur at least 20 years ahead, we assumed that recycling rate for the major material will be improved and about 70% of steel and of aluminium and glass will be recycled. (As it is hard to obtain any data available on the recycling technology of auxiliary materials, we did not consider their recycling in our study).

Manufacturing and disposal of BOS such as inverter, separator, heat exchanger, feed pump, supporting structure and their accessories are also included in the LCA boundary (see Figure 4). The transportation of all necessary components to the final assembly site and transportation to the landfill at the end of the life of the system have also been taken into account. It is assumed that average distance for components transportation is 300 km and to the final disposal is 100 km. (All transportations are assumed to be done by road diesel trucks with the capacity of 20 tons).

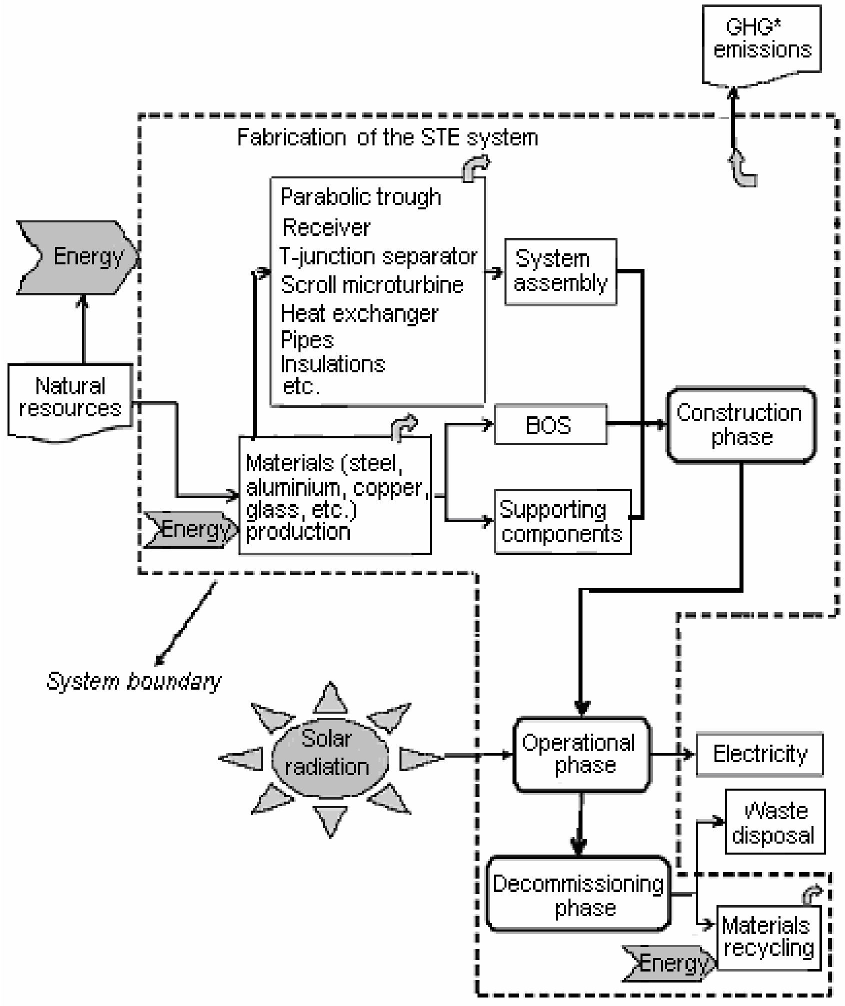

Figure 4. The LCA boundary of the small scale solar thermal electricity generation system.

At the use stage of the STE system, little so-called "parasitic" electric loads are necessary. The "parasitic" electric loads are the motor for the heat transfer fluid (HTF) pump and motor for PTC tracking mechanism. Additional parasitic load is a control unit. The estimated parasitic electric loads based on presented above data is 0.4 kW (0.1 kW – motor for HTF pump; 0.25 kW – for PC tracking device; 0.05 kW – for control unit). Also, to maintain proper reflectivity of PTC (about 0.95) washing water has to be used. According [7] mirror wash water consumption is 0.022 $m^3/(m^2 \cdot year)$. However, detergent use is not considered.

We also assume that 10% of HTF to be replaced each year due to some losses, which translates to an additional consumption of 6,4 kg of ammonia over the life time of operation of the STE system.

As the proposed STE system mostly made from metals, at the end of its life the STE system will be disabled and materials will be recycled based on the current recycling rate [17 - 19] and trends: aluminium – 60%; steel, copper – 70%; plastic – 50%. Recycling of glass module sheets represents some problems, because glass contaminated with plastics (more than 100 g per ton of glass) is normally not accepted. However, in this study we assumed that in 20 years the most problems of glass recycling will be solved, so 70% of glass is recycled, as well. We also assumed that 50% of metal and plastic components from BOS will be recycled [17]. We assume the rest of materials after removal of the materials to be recycled are disposed of as a solid waste at landfill.

4 Materials and energy analysis and GHG emissions

The list of materials required directly or indirectly for the life cycle of the proposed STE system has been obtained through SimaPro8.0 modelling [16] based on inventory data. Table 1 shows the amount of required materials for the whole life cycle of the STE system. As can be seen from data presented in Table 1 dominating resources are metal ores (iron, copper, bauxite), fossil fuels (coal, natural gas, crude oil) and commodities for glass making (calcite, limestone, gravel). Other resources presented in Table 1 are mostly used as alloying metals for steel making, including stainless steel and for glass mirrors coating (silver). Obtained results for primary energy consumption and GHG emission through whole life cycle of the STE system presented in Table 2.

Table 1. Resources required for the full life cycle of adopted STE system

Substance	Unit	Total
Bauxite in ground	kg	25.7
Copper in ground	kg	34.6
Iron in ground	kg	592.1
Zinc in ground	kg	6.3
Lead in ground	g	100.3
Magnesium in ground	g	597.7
Manganese in ground	g	111.2
Molybdenum in ground	g	67.2
Nickel in ground	g	840.7
Silver in ground	g	60.0
Calcite in ground	kg	100.24
Limestone in ground	kg	8.336
Gravel in ground	kg	170.9
Sodium chloride in ground	kg	29.9
Coal hard in ground	kg	6143.0
Natural gas in ground	m^3	248.0
Oil crude in ground	kg	100.0
Water unspecified	m^3	3203.0

Based on the presented results and made assumptions and methodology adopted in [17], the energy and greenhouse gas (GHG) emissions payback, the energy and GHG emissions payback time have been calculated for where whole life cycle of adopted STE system:

The energy payback time is:

$$PBT_{\mathrm{E}} = \frac{E_{\mathrm{C}} \cdot p}{(E_{\mathrm{P}} - E_{\mathrm{L}})/t} = \frac{32.5 \cdot 0.35}{(590-79)/20} = 0.45 \text{ (year)},, \tag{2}$$

where, E_{C} is total energy consumption through whole life cycle of the STE system; $p = 0.35$ is adopted within the study efficiency of conversion primary energy to electricity (including transmissions loss); E_{P} and t are total energy production of the system and the life time of the system; E_{L} is parasitic electric load (the energy consumed for the system's own needs).

The GHG payback time is:

$$PBT_{\mathrm{GHG}} = \frac{t\,.\,{}^{T_{\mathrm{GHG}}}\!/\!_{c}}{E_{\mathrm{P}} - E_{\mathrm{L}}} = \frac{20\,.\,{}^{10044}\!/\!_{262}}{590 - 79} = 1.95 \text{ (year), ,} \tag{3}$$

where T_{GHG} is total GHG emissions through whole life cycle of the STE system (see Table 2); c is the GHG average emissions per 1GJ of produced electricity in Australia (c = 262kg of CO_2 eq. per 1GJ [16]).

Table 2. The primary energy consumption and GHG

Processes (Components)	Primary Energy (MJt)	GHG Emissions (kg CO_2 eq.)
Parabolic Trough	16931	731.5
Solar Reflectors	192	131.2
Receiver	2952	177.2
Micro-turbine	6630	4944.5
Separator	91	61.0
Heat Exchanger	162	108.5
Water Pump	271	195.3
Pipes	369	75.8
Insulation	7	27.7
Inverter	1306	919.5
Control Unit	593	524.9
Tracking Mechanism	482	270.0
Woking Fluid	46	1.3
Miscellaneous	1613	1112.0
Use Stage	83	2.0
Disposal	261	19.9
Total	31989	9302.3

5 Conclusions

The LCA case study and results obtained for STE generation system for Australian conditions indicates a big potential of such systems in term of their environmental performance. It has been shown that proper design can bring about 20% efficiency of conversion of solar energy to electricity. Such rather high efficiency can be even substantially increased if integrated solar combined (heat-power or cooling-heat-power) generating is installed.

Although the presented case study has an intrinsic uncertainty and assumptions related to various factors (lack of detail information sources, data quality, etc.), however, it clearly shows the order of magnitude of energy consumption and GHG emissions ascribable to the whole life cycle of STE system.

An important insight from this study is the significance of the impacts at life cycle stages. Both energy consumption and GHG emissions are highest for manufacturing and assembly of the main components. Comparatively, impact from both use and disposal stages are negligible (less than 1%).

Further, the great energy and environmental advantage of the system are shown by very low values of payback times (less than a year for energy and less than 2 years for GHG). Even including the variability related to raw material eco-profiles and the uncertainties regarding different life cycle steps, it has been estimated that in pessimistic scenarios, the payback times are less than 4 years. Such results state a positive qualitative judgement for the environmental performances of the small scale solar thermal electricity production system that is not sensibly influenced by all the study uncertainties

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