Performance Analysis of a Conventional and Renewable Energy based Electric Power Generation Systems – A Comparative LCA Study

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Abstract. Electricity, a readily usable form of energy is much in demand in developing countries like India due to the increase in human population and their improved lifestyles. One of the criteria to achieve the developed country tag is per capita consumption of electricity. It means that all developed countries have energy-intensive economies. With climate change effects are coming into fore, countries started scrutinizing the sources of energy and electricity too. Resource intensive traditional or conventional sources of energy with matured technologies on one side and alternative energy technologies that include renewable with developed or yet to fully developed technologies on the other side are competing for electricity pie in almost in every country. This study adopts the Life Cycle Assessment methodology to determine the energy efficiency and environmental impact assessment of two competing electric power generation systems, one based on conventional energy source and another one based on the renewable energy source. It is a common knowledge that renewable systems have better energy efficiency as they do not consume fuel energy as input and also have lower carbon emissions. This study projects what extent they are better for a unit of electricity produced by both competing systems in terms of predefined metrics such as ERR/EPBT, GWP and GWMP in terms of CO₂ equivalents and Green Rating for comparative purposes. The study results may be useful for policymakers as a component in the comprehensive decision-making process for energy planning to meet the future human need or greed for electricity with sustainability and also to achieve circular economy goals.

Keywords: Life Cycle Assessment (LCA), Net Energy Analysis (NEA), Energy Pay Back Time (EPBT), Energy Return Ratio (ERR), Global Warming Potential (GWP) and Global Warming Mitigation Potential (GWMP).

1. Introduction

Electricity mix in India is Coal dominant, as it stands, it is about 70% of total electricity generated [1]. Only 20% of the total electricity generated based on renewables like Hydro, Wind, Solar and Biomass. Rest of 10% is either Gas or Nuclear based electricity. Even individual states like Andhra Pradesh and Telangana also have coal-dependent electricity mixes.

So, in short, the Indian economy is a carbon-intensive one. India as a signatory of the Paris Agreement on climate change has to look beyond Carbon-based Coal as a source of electric power generation. As per a pledge by India in the recent COP 21 convention on climate change, at least 40% of the country’s electric power generation capacity should be based non-fossil fuels by 2030.
But Coal is still a dominant and more reliable source of energy as it continues to contribute majorly to India’s energy pie in the immediate future. With a proclaimed very high low-carbon advantage of alternative systems that include renewables over conventional options for generating electric power, an attempt was made to carry out a holistic study of it by a standardized LCA methodology to determine the extent of it.

2. Methodology

LCA an abbreviation to a methodology known as Life Cycle Assessment is an analytical tool whose definitions, fundamental concepts, all methodological aspects and applications are described in the ISO 14040 – 14049 series of standards. It evaluates the energy performance and environmental impacts Assessment over the life-cycle of a product, process or a system from birth to death. Net Energy Analysis (NEA) of a system, together with the evaluation of a system’s environmental impacts is also referred to as Life Cycle Assessment. It is one of the performance evaluation techniques which seeks to compare the amount of energy delivered in the more readily usable form by technology to the total energy required to discover, extract, process and deliver or otherwise to upgrade that energy into a socially useful form.

![Figure 1. Stages & Applications of LCA as a Methodology](image)

Figure 1 depicts the various stages in the LCA framework and intended applications of it [2]. Here it is applied to two competing systems, both of which generate electricity. LCA methodology has certain limitations.

- Resource-intensive and time-consuming nature of LCA studies;
- Uncertainty in the quality of available data makes the results of LCA uncertain in many cases;
- As some of the impacts are not covered, the boundary is not broad enough makes the scope of LCA study, incomplete;
- Analysis is static in nature as technological progress is not to reflect in results;
- Method itself is static in nature.
3. Case Study

In this case study, a 950 kWp grid-connected, rooftop Solar PV based electric power plant proposed to set up at Bharat Biotech located in Shamirpet, Hyderabad and a 500 MW operating unit of Dr Narla Tata Rao Coal based Thermal Power Plant, Vijayawada in Andhra Pradesh are in contention for carrying out a comparative LCA study. Both the systems were modelled and run on SimaPro 9.0.0.48 LCA software with ecoinvent 3.0 as the database.

3.1. Goal & Scoping

It is the initiation step of any LCA study. Here, a comparative study between two systems, one a conventional coal-based and another renewable energy-based with a kWh produced by both the systems as a functional unit (FU) for determining their energy performance and environmental impact assessment in terms of predefined metrics. The scope covers all the energy and material inputs and environmental emissions corresponding to the entire life cycle stages of both systems that may include fuel or raw material extraction and all transport processes involved. The time horizon for this study is selected for both the systems as 25 years of plant lifetime.

3.2. Inventory Analysis

The second and most critical stage of any LCA study is Inventory Analysis. It covers the data collection and compilation of material and energy inputs, emissions and product outputs for the complete life cycle of those systems, selected for the study. The primary task in this stage is the creation of a process flow diagram which will serve as the blueprint for the inventory data to be collected.

![Figure 2. Sample Process-Flow diagram prepared for Solar PV System](image-url)
For the modeling purpose in the LCA, the entire system is divided into easily identifiable unit processes so that there is a sort of convenience in the data collection. Later, these unit processes are grouped into upstream, operational and downstream processes to reduce the complexity in presenting the process flow diagrams shown in Figure 2. The data collected is further processed for 1kWhe as an outcome of inventory analysis carried out for the selected 500 MW Coal based electric power generation system and sample data collected and processed for a conventional coal system is tabulated as shown in Table 1.

### Table 1. Resource Consumption

| Resource/Inventory        | Amount [ / kWh] | Data Source                  | Remarks            |
|--------------------------|-----------------|------------------------------|--------------------|
| Coal [kg]                | 5.65E-01        | Calculated                   | --                 |
| Water [kg]               | 3.10E+00        | Power Plant                  | --                 |
| Water [m³]               | 3.00E-01        | -do-                         | cooling circuit    |
| Electricity, medium voltage [kWh] | 5.00E-02 | -do-                         | to run auxiliaries |
| Light Fuel Oil [kg]      | 2.60E-04        | ecoinvent Database           | --                 |
| 500 MW Coal Power Plant [p] | 1.17E-11   | Calculated                   | with data from another Table. |

#### 3.3. System Modelling

Both the identified systems are modelled on SimaPro LCA software with the collected data during inventory analysis.

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**Figure 3.** System Model of a 500 MW Coal based Electric Power Generation System in SimaPro with cut-off value of 0.1% / CED Method

Figure 3 is the network representation of a 500 MW Coal based electric power generation system when it is modelled and run on SimaPro LCA software by using an inbuilt Cumulative Energy Demand (CED) method with ecoinvent as the database. It will give us the input energy required by the system to generate a kWh of electricity and ultimately the energy performance of the system.
Figure 4. System Model of a 950 kWp SPV based Electric Power Generation System in SimaPro with cut-off value of 0% / IPCC 2013 GWP 100a Method.

Figure 4 is the network representation of a 950 kWp SPV based electric power generation system when it is modelled on SimaPro LCA software and run by using a single-issue IPCC 2013 GWP 100a method with ecoinvent as the database. It will give us the environmental impact assessment of the system in terms of kg CO2 Equivalents to generate a kWh of electricity.

3.4. Results based on Predefined Metrics:

Energy Performance Metrics:

Energy Pay Back Time (EPBT) is the time required to recover the Indirect Lifetime Energy Inputs in primary energy terms in all the life cycle stages of a system including embodied energies in materials and A.C. power [3]. This term ‘EPBT’ is generally used by energy policymakers for the renewable systems only as they don’t have any direct fuel energy inputs.

Renewable System:

Energy Payback Time (EPBT) = CED / AEO

= 2.82E7 / 6,314,840

= 4.46 Years
Electricity generated by the system during its lifetime (LEO) = 294.8 Wp (at PTC) x 2,964 (no. of panels) x 25 years x 365 days x 5.5 (avg. operating hours) = 43,853,195.1 kWh

Annual Electricity Output (AEO) = LEO / 25 = 1754122.2 kWh

Energy Return Ratio (ERR) is a ratio of useful electrical output to the sum of primary energy inputs supplied (CED) to the system in all its life cycle stages during its lifetime [4].

Conventional System:

Energy Return Ratio (ERR) = FU / CED
= 1×3600 / 12×1000 = 0.3 (30 %)

Renewable System:

Energy Return Ratio (ERR) = LEO / CED
= 157871000 / 28200000
= 5.6

Environmental Impact Assessment (EIA) Metrics:

Green House gases like Carbon Dioxide (CO₂), Methane (CH₄) and Nitrous Oxide (N₂O) cause global warming. For example, CH₄ has 25 times more Global Warming Potential than CO₂ [5]. So, cumulative Global Warming Potential [4] of all greenhouse gases emitted from the electricity generations expressed as a single Score in terms of CO₂ Equivalents per kwh generated.

Conventional System:

Global Warming Potential (GWP) = Life-Cycle CO₂ Equivalent Emissions / FU
= 1.32 kg CO₂e / kWhₑ

Environmental Score/ Green Rating
= Baseline Emissions per kWhₑ generated as per CEA [6] / Actual Emissions per kWhₑ
= 0.944 / 1.320 = 0.715

Renewable System:

Global Warming Potential (GWP) = Life-Cycle CO₂ – Equivalent Emissions / FU
= 0.0393 kg CO₂e / kWhₑ

Environmental Score/ Green Rating
= Baseline Emissions per kWhₑ generated as per CEA [6] / Actual Emissions per kWhₑ
= 0.944 / 0.0393 = 24
4. Analysis based on Comparative Results

Table 2. Comparative Results

| EPGS               | EPBT in Years | ERR | GWP in kg CO\textsubscript{2}e | Green Rating |
|--------------------|---------------|-----|------------------------------|--------------|
| Conventional Coal Thermal | NA            | 0.30| 1.320                        | 0.715        |
| Renewable Solar PV | 4.46          | 5.6 | 0.0393                       | 24           |

Figure 5. Bar Chart depicting the Comparative Results

*Global Warming Mitigation Potential for Renewable System:*
Reduction in Global warming potential due to avoidance of more release of greenhouse gases into the atmosphere by adopting Renewable SPV system in place of Conventional Coal-based electric power generation system is known as Global Warming Mitigation Potential of the Renewable System.

Global Warming Mitigation Potential

\[ \text{Global Warming Mitigation Potential} = \text{LEO in kWh} \times (\text{GWP of Conventional System} - \text{GWP of Renewable System}) \]

\[ = 43,853,195.1 \times (1.320 - 0.0393) / 1000 = 56,162.787 \text{ tons of CO}_2\text{e over a system’s lifetime of 25 Years.} \]
From Table 2, it is quite evident that conventional Coal-based electric power generation system will never be able to pay back the energy consumed in all its life cycle stages over its lifetime as it has an ERR of only 0.3 (<1). It is because these systems consume direct fuel energy or primary energy which in turn gets converted into secondary thermal energy, with a mere 30 - 40% efficiency. If all other conversion efficiencies and the energy consumed for coal mining and transport processes are also taken into account, then the system’s ERR ends up at 30% (0.3) only. Renewable SPV system has a healthy ERR of 5.6, which means the system is a net energy provider and the energy return is 5.6 times that of energy consumed in all its life cycle stages over a time horizon of 25 years.

As the Coal is a Carbon-based fuel, its combustion will release Greenhouse gases. So, Coal based electric power generation system releases about 1000 g CO₂ Equivalents for each unit of electricity (kWhₑ) produced by the system as estimated by some of the studies in the Indian context. As this study has Coal Mining and Transport processes are also within its boundaries, the GWP of the system is estimated to be around 1320 g CO₂ Equivalents per functional unit of the study. From Figure 5, it appears to us that renewable SPV system has zero GWP. But it also does have GWP which is 33 times lesser for each unit of electricity generated in comparison. Generation of electricity by a renewable system instead of the conventional coal-based system avoids a significant amount of GHG emissions which can be termed as Global Warming Mitigation Potential and it is about 56,000 tons over a lifetime of 25 Years. By comparing with a value of baseline emissions in g CO₂ Equivalents for each unit of electricity generated in India as fixed by CEA, the green rating of renewable SPV system is estimated at 24.

5. Improvement Analysis:
The intended use of life cycle assessment studies is to identify the opportunities to reduce the environmental burden of a system through improvements in process design or by using substitute materials that may result in a system more friendly to the environment. Renewable SPV system’s 90 % indirect Lifecycle Energy Inputs and 88 % of GHG emissions are during materials and system construction phases of the life cycle, so the attention must be on those life cycle stages to improve environmental performance and also for a reduced EPBT. Addition of End of the Life (EOL) disposal scenarios with recycling as an integral part of them, during the modelling phase may make a positive impact on the energy & environmental performance of the system. Technological improvements like the advances in PV cell technology may further improve the conversion efficiencies and in turn, improves the energy & environmental performance of renewable SPV system. The dependence on coal for electric power generation is set to continue in India for few more decades, the adoption and implementation of Super Critical Technology and Integrated Gasification Combined Cycle (IGCC) technologies are essential to improve the overall performance of conventional Coal-based electric power generation systems. Use of judicious energy mix as inputs to the system during various life cycle stages of it supposedly improves the system’s overall performance.

6. Summary & Conclusions:
The LCA results are sensitive to varying energy mix as input to the systems. The results of two LCA studies might differ from one another because of the scope of those LCA studies with the same goal might be different and also due to site-specific characteristic of LCA. Nameplate capacities of both the systems compared in this study are quite different. But the results are presented here for a functional unit selected for the study which is same for both the systems. The nameplate capacity of renewable
SPV systems can’t be raised inadvertently because land-based systems require a large area and rooftop systems distributed over several buildings for higher nameplate capacity will rise the inventory requirements. Overall, renewable systems have a lower carbon footprint and are positive net energy producers.

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