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# Economic And Environmental Analyses Of A 10kwe Low Temperature Solar Thermal Power Plant

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***Abstract***

This aspect of the study is meant for the evaluation of the economic and environmental performance of the 10 kWe low temperature solar thermal energy conversion plant. It is part of a study to evaluate the feasibility of low temperature solar thermal energy conversion system based on the organic Rankine cycle (ORC) as a viable means of generating clean and environmentally sustainable electricity. The study was conducted at University of KwaZulu-Natal (UKZN), Durban, South Africa. The study is presented in two sections; the first being on the economic analysis and the second on the environmental analysis. The Cost-Benefit Analysis is used for the economic analysis and its output is in the form of Net Present Value (NPV) and Rate on Investment (ROI); the Life Cycle Analysis (LCA) method is used for the environmental analysis and its output is in the form of Carbon Pay Back Period (CPBP) and Carbon Intensity. Two other parameters are determined and may aid in assessing both the economic and the environmental performances and they are Energy Pay Back Period and Energy Intensity.

## *1. Introduction*

Economic and environmental positivity’s emanating from wider access to clean energy have been deliberated at length by several researchers and other personalities; they include improved standards of living (cleaner indoor environments, HVAC, lighting, cooking, food storage, telecommunication and entertainment) and improved industrial production (employment, production of consumer and industrial goods); environmental benefits include reductions in carbon emissions (normalising or reduced global warming, reduction in climate change, and less ozone layer depletion), reductions in exposure to radioactive radiation, and reduced degradation of local environments (low air pollution, low water pollution).

The analysis in this paper will attempt to qualitatively and quantitatively establish the environmental and economic performance of the 10kW low temperature solar thermal power concept plant.

## *2. 10kW Concept Plant Design*

The plant consists of a solar field, pumps and field piping, storage tank, a complete IT10 ORC plant supplied by Infinity Turbine and a cooling tower. A schematic representation of the concept plant is shown in figure 1.

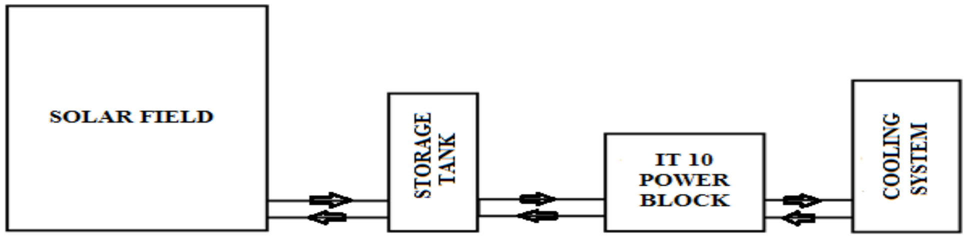


Figure 1: schematic representation of the final concept plant

The land requirement maybe calculated accurately taking into account geographical position of the field, shading, aperture area of the collectors and their orientation together with an analysis of the thermal losses from the field piping; however, as a general rule of thumb the size of land can usually be estimated by multiplying the total aperture area of the solar collectors by a factor of 2 to 3.5 [1]. For this concept plant with 180 solar collectors of 1840x1650 mm size, the area maybe estimated as 180x1.84x1.65x2.5 giving 1366.2 m$^2$. Allowing for spacing between the two fields, figure 12.2, and taking into account the space for the storage tank, cooling system and the IT10 ORC unit, a rough estimate of 1500m$^2$ of a piece of land 50m in length and 30m in width is considered adequate; a suitable remotely located, unused or disused cheap land would be attractive for this work; cost of the land estimated ZAR 50,000 to ZAR 100,000.

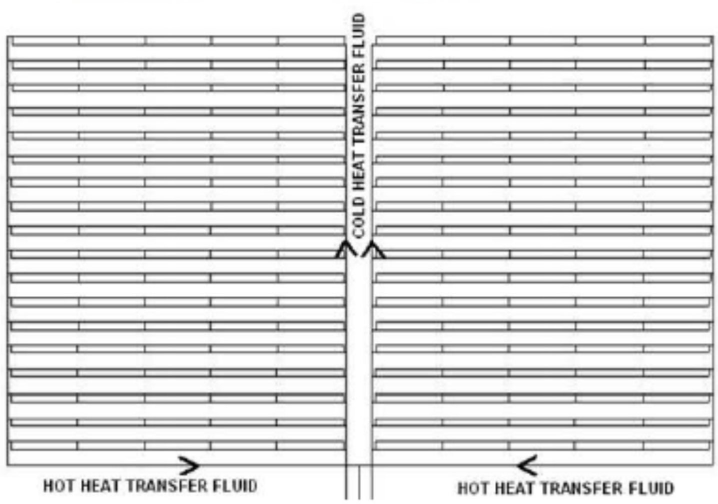


Figure 2: Layout for 180 solar collectors of the 10kWe solar field

Cost of the solar collectors: ZAR 1 260 000.00 (Solardome: SPX 3.0 Vertical: Solar Heating Collectors, Product code: SHC-S-SPX3.0-H, 1840 x 1650 x 76mm; price per collector Incl. Tax: R7, 000.00)

Cooling system: a small, compact, mechanical draught, dry cooling tower with a 44 gpm (gallons per minute) capacity is considered appropriate for this level of operation; more accurate design, modelling and optimized system can be developed. The cost is estimated as USD25-USD40 per gpm as initial investment and about USD6-USD10 per year per gpm as energy cost of operation. Cost of cooling system: USD 1500.00 ≈ ZAR 20 000 (September 11, 2015) [2].

Pumping system: the pump cost required is for the solar field; the ORC unit comes complete with a feed pump while that for the cooling system is included in the cooling system cost estimates; solar field pump cost estimate: ZAR 5000. A combined pumping operational cost estimate will be adopted in the economic analysis ≈ ZAR 12000 per year.

Field piping: high pressure, heat resistant, water flow pipe (PVC, flexible rubber hose, etc.) cost about USD 0.25 per meter; about 1500 meters required. Cost: USD 375 ≈ ZAR 5000 [3].

Frame structure support for solar collectors (2000m of 30x30x4mm galvanised steel angle iron): estimate ZAR 100 000

Cost of ORC unit: USD 51 500 ≈ ZAR 600 000

Working fluid: 58 kg of R134a (or 245fa); ZAR 4000 for 60 kg R134a.

Storage with pumping accessories: estimated ZAR 10,000.

Table 1 Cost Compilation for the 10 kWe Solar Thermal Power Plant

| **Component** | **Unit Price** | **Quantity** | **Sub-Total** |
|---|---|---|---|
| Land | | 50 m x 30 m | 100 000 |
| Solar Collectors | 7 000 | 180 | 1260000 |
| Cooling Tower | | 01 | 20 000 |
| Pumps | | 03 | 5000 |
| Storage | | 01 | 10 000 |
| Field Piping | | PVC/Rubber Hose/PERT | 5000 |
| Frame Structure | | 30x30x4 mm Galvanised Steel | 100 000 |
| IT10 ORC Unit | | 01 | 600 000 |
| Working Fluid: R134a | | 58kg | 4000 |
| Labour | | | 100000 |
| | | **Total** | ZAR 2 214 000 |

The price of electricity would normally be determined during the bidding process. For this analysis however tariffs obtained from the eThekwini Single-Phase Tariffs will be used; that is R1.3146/kWh [4]

## *3. Economic Analysis*

Cost-benefit analysts typically use one of several metrics - or a combination of them - to report their findings. The benefit-cost ratio, return on investment and net present value report the results of a cost-benefit analysis by comparing discounted costs with discounted benefits.

**Benefit-Cost Ratio (BCR):** directly compares benefits and costs. To calculate the BCR, divide total discounted benefits by total discounted costs.

$$BCR = \frac{Total\ Discounted\ Benefits}{Total\ Discounted\ Costs} \qquad [1]$$

**Return on Investment (ROI):** compares the *net benefit* (total discounted benefits minus total discounted costs) to costs. To calculate the ROI, first calculate the net benefits and then divide the net benefits by the total costs; expressed as a percentage.

$$ROI = \frac{(Total\ Discounted\ Benefits - Total\ Discounted\ Costs)}{Total\ Discounted\ Costs}; (\%) \qquad [2]$$

**Net Present Value (NPV):** reflects the net benefits of a project in ‘dollar’ terms. To calculate NPV, subtract the total discounted costs from the total discounted benefits.

$$NPV = Total\ Discounted\ Benefits - Total\ Discounted\ Costs \qquad [3]$$

The formula for the NPV is as shown:

$$NPV = -I_{TOTAL} + \sum_{i=0}^{n} \frac{B}{(1+d)^n} \qquad [4]$$

Where:

$I_{TOTAL}$ = total investment cost
B = yearly benefits of the 10kW solar plant
d = discount rate
n = number of years

The yearly benefits can be measured in several terms, i.e. avoided electricity costs, avoided wood fuel usage etc. To simplify the matter we adopt the former.

In this model we use a simplified equation for the NPV after ‘n’ years:

$$NPV = -I_{TOTAL} + \frac{B}{d}\left(1 - \frac{1}{(1+d)^n}\right) \qquad [5]$$

The value of the discount rate is taken from analogous case studies. It has assumed value of 5%.

**Energy Pay Back Period (EPBP):** The energy benefit can be determined by Energy Pay Back Period (EPBP) which is given by the equation:

$$\text{EPBP} = \frac{\text{Energy consumed by power plant (kWh)}}{\text{Energy produced by power plant per year (kWh)}} \quad [6]$$

**Energy Intensity:** This energy benefit may also be represented by the energy intensity given by the equation:

$$\text{Energy Intesnity} = \frac{\text{Total Input Energy (kWh)}}{\text{Life Time Electricity Production (kWh)}} \quad [7]$$

## 4. *Environmental Analysis*

The environmental analysis was done based on the **Life Cycle Analysis (LCA)** method which is a 'cradle to grave' analysis of environmental impacts, net energy and cost [5]. The following, figure 2, shows an LCA schematic representation of a solar power plant.

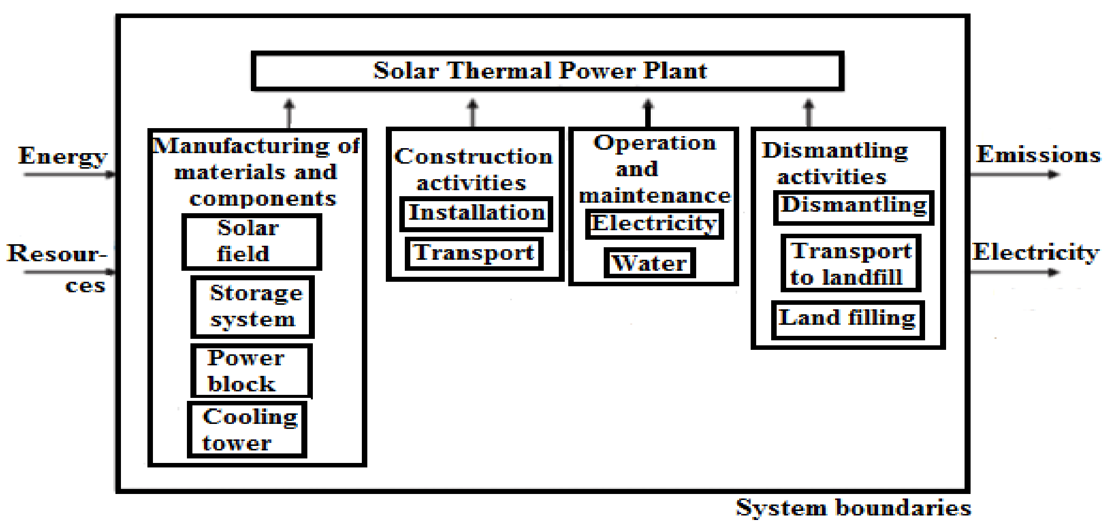


Figure 2: Life cycle of a solar thermal power plant

The environmental performance can be indicated by the Carbon Intensity and the Carbon Pay Back Period

**Carbon Pay Back Period (CPBP)**: is a measure of how long a CO2 mitigating process needs to run to compensate the CO2 emitted to the atmosphere during the life cycle stage. The formula used is:

$$\text{CPBP} = \frac{\text{Life Cycle } CO_2 \text{ emission}}{\text{Gross } CO_2 \text{ emission avoided per year}} \text{ x } 365 \qquad [8]$$

**Carbon intensity**: is the carbon emission associated with the manufacturing, operation and decommissioning of the power plant per unit of electricity produced over the life time. It is given by the equation:

$$CO_2 \text{ Intensity} = \frac{\text{Life Cycle } CO_2 \text{ emission (g of } CO_2)}{\text{Life time electricity generation (kWh)}} \qquad [9]$$

## 5. *Calculations*

Notes regarding data used to perform analyses:

- Power Cost Calculations: price of electricity = 136c/kWh; increase in price per year = 15%; discounted rate = 5% [4]
- R134a is very attractive as a refrigerant because it has zero ozone depleting potential as well as a low direct global warming potential (GWP). [6]
- IT10 unit: 181 kg (un-crated); without proper data we assume the IT10 unit consists 90% steel and associated alloys; 2.5% copper; 2.5% aluminium and associated alloys; 2.5% rubber hoses; and 2.5% other metals.
- Power generated and Emissions Avoided: emissions avoided (Eskom average Emission Factor 1.015 kg CO2-eqt/kWh)*power generated from IT10 plant per annum =30000kWh/annum: 30450 kg $CO_2$-eqt/annum. [7]
- Pump power estimated at 1% of produced power [8]: emissions 304 kg CO2/annum; power 300 kWh/annum.

Table 2 shows the breakdown of cycle component prices under the current scenario where the power block is imported from Infinity Turbine and priced at R&D rates:

Table 2 cycle component prices

| **Component** | **Unit Price** | **Quantity** | **Sub-Total** |
|---|---|---|---|
| Land | | 50 m x 30 m | 100 000 |
| Solar Collectors | 7 000 | 180 | 126000<br>0 |
| Cooling Tower | | 1 | 20 000 |
| Pumps | | 3 | 5000 |
| Storage | | 1 | 20 000 |
| Field Piping | | PVC/Rubber Hose/PERT | 5000 |

| | | | |
|---|---|---|---|
| Frame Structure | | 30x30x4 mm Galvanised Steel | 100 000 |
| IT10 ORC Unit | | 1 | 600 000 |
| Working Fluid: R134a | | 58kg | 4000 |
| Labour | | | 100000 |
| | | **Total** | 2 214 000 |

The NPV computations are done using Ms Excel spreadsheet. The results are shown in table 3.

Table 3 NPV computations

| **Year** | **Year** | **System Cost** | **Annual Cash Flow (ZAR)** | **NPV of Annual Cash Flow (ZAR)** | **Cumulative NPV (ZAR)** |
|---|---|---|---|---|---|
| 0 | 2015 | -2 214 000 | 0.00 | 0.00 | -2 214 000.00 |
| 1 | 2016 | | 40392.00 | 38468.57 | -2 175 531.43 |
| 2 | 2017 | | 46450.80 | 42132.24 | -2 133 399.18 |
| 3 | 2018 | | 53418.42 | 46144.84 | -2 087 254.34 |
| 4 | 2019 | | 61431.18 | 50539.59 | -2 036 714.76 |
| 5 | 2020 | | 70645.86 | 55352.88 | -1 981 361.88 |
| 6 | 2021 | | 81242.74 | 60624.58 | -1 920 737.29 |
| 7 | 2022 | | 93429.15 | 66398.35 | -1 854 338.94 |
| 8 | 2023 | | 107443.52 | 72722.01 | -1 781 616.94 |
| 9 | 2024 | | 123560.05 | 79647.91 | -1 701 969.03 |
| 10 | 2025 | | 142094.06 | 87233.43 | -1 614 735.60 |
| 11 | 2026 | | 163408.17 | 95541.37 | -1 519 194.23 |
| 12 | 2027 | | 187919.39 | 104640.55 | -1 414 553.68 |
| 13 | 2028 | | 216107.30 | 114606.32 | -1 299 947.36 |
| 14 | 2029 | | 248523.40 | 125521.20 | -1 174 426.16 |
| 15 | 2030 | | 285801.91 | 137475.60 | -1 036 950.55 |
| 16 | 2031 | | 328672.19 | 150568.52 | -886 382.03 |
| 17 | 2032 | | 377973.02 | 164908.38 | -721 473.66 |
| 18 | 2033 | | 434668.98 | 180613.94 | -540 859.72 |
| 19 | 2034 | | 499869.32 | 197815.26 | -343 044.45 |
| 20 | 2035 | | 574849.72 | 216654.81 | -126 389.64 |

Sensitivity analyses are also performed based on the assumption that the turbine unit and solar collectors are locally made at half prices (and cheap land is available) and the results are shown in table 4.

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Table 5 shows computations for environmental analysis.

The two main references (databases) used as sources of information for embedded energy and carbon emissions are *Emission factors in kg CO2-equivalent per unit* [9] and *Inventory of Carbon and Energy (ICE) Summary* [10].

## *6. Results*

The results metrics are presented below:

Energy consumed by power plant (kWh) = 300 kWh/annum

Energy produced by power plant per year (kWh) = $30000 kWh/annum$

Total Output Energy (kWh) = 29700kWh/annum

Life Time Electricity Production (kWh) = $X\ 20\ years = 594000kWh$

Table 4 NPV computations – Sensitivity Analysis:

| Year | Year | System Cost | Annual Cash Flow (ZAR) | NPV of Annual Cash Flow (ZAR) | Cumulative NPV (ZAR) |
|---|---|---|---|---|---|
| 0 | 2015 | -1 234 000 | 0.00 | 0.00 | -1 234 000.00 |
| 1 | 2016 | | 40392.00 | 38468.57 | -1 195 531.43 |
| 2 | 2017 | | 46450.80 | 42132.24 | -1 153 399.18 |
| 3 | 2018 | | 53418.42 | 46144.84 | -1 107 254.34 |
| 4 | 2019 | | 61431.18 | 50539.59 | -1 056 714.76 |
| 5 | 2020 | | 70645.86 | 55352.88 | -1 001 361.88 |
| 6 | 2021 | | 81242.74 | 60624.58 | -940 737.29 |
| 7 | 2022 | | 93429.15 | 66398.35 | -874 338.94 |
| 8 | 2023 | | 107443.52 | 72722.01 | -801 616.94 |
| 9 | 2024 | | 123560.05 | 79647.91 | -721 969.03 |
| 10 | 2025 | | 142094.06 | 87233.43 | -634 735.60 |
| 11 | 2026 | | 163408.17 | 95541.37 | -539 194.23 |
| 12 | 2027 | | 187919.39 | 104640.55 | -434 553.68 |
| 13 | 2028 | | 216107.30 | 114606.32 | -319 947.36 |
| 14 | 2029 | | 248523.40 | 125521.20 | -194 426.16 |
| 15 | 2030 | | 285801.91 | 137475.60 | -56 950.55 |
| 16 | 2031 | | 328672.19 | 150568.52 | 93 617.97 |
| 17 | 2032 | | 377973.02 | 164908.38 | 258 526.34 |
| 18 | 2033 | | 434668.98 | 180613.94 | 439 140.28 |
| 19 | 2034 | | 499869.32 | 197815.26 | 636 955.55 |
| 20 | 2035 | | 574849.72 | 216654.81 | 853 610.36 |

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Total embedded energy equals 635754.418 MJ or 176598.45 kWh

Gross $CO_2$ emission avoided per year = 30146kg

Life Cycle $CO_2$ emission = 35258.6 kg

Life Cycle $CO_2$ emission (g of $CO_2$) = 35 258 690 $g$

$$\text{Return on Investment (ROI)}: = \frac{(126389.64)}{2214000} = -0.057$$

$$\text{Return on Investment (ROI) - Sensitivity Analysis}: = \frac{853610.36}{2214000} = 0.386$$

Net Present Value (NPV): = ZAR–126 389.64 or ZAR (126 389.64)

Net Present Value (NPV) – Sensitivity Analysis: = ZAR 853 610.36

Table 5 environmental analysis:

| **Component** | **Description** | **Mass (kg)** | **Embedded Energy Index (MJ/kg)** | **Embedded Energy Content (MJ)** | **Embedded Carbon Emissions Index ($kgCO_2eq/kg$)** | **Embedded Carbon Emissions Content ($kgCO_2eq$)** |
|---|---|---|---|---|---|---|
| **IT10** | Steel | 162.9 | 24.4 | 3974.76 | 1.77 | 290 |
| | Copper | 4.525 | 50 | 226.25 | 2.77 | 12.5 |
| | Aluminium | 4.525 | 155 | 701.375 | 8.14 | 36.8 |
| | Rubber hose | 4.525 | 101.7 | 460.1925 | 3.18 | 14.4 |
| | Others | 4.525 | - | | 4.4 | 19.9 |
| | | **Sub-Total** | | **5362.5775** | | **373.6** |
| **Solar Field** | Galvanised steel 30x30x4 mm | 3768 | 24.4 | 91939.2 | 1.77 | 6670 |
| | 0.5mm Galvanised steel casing | 2200 | 24.4 | 53680 | 1.77 | 3894 |
| | 4mm Solar Glass | 5720 | 15 | 85800 | 0.85 | 4862 |
| | 40mm Insulation | 1400 | 45 | 63000 | 1.86 | 2604 |
| | 15mm Copper pipes | 3263 | 50 | 163150 | 2.77 | 9038 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 0.5mm Copper absorber | 2500 | 50 | 125000 | 2.77 | 6925 |
| | Rubber hose | 60 | 101.7 | 6102 | 3.18 | 190 |
| | Black paint | 50 (546.48 $m^2$) | 68 (/$m^2$) | 37160.64 | 3 | 150 |
| | Other | | - | | | ignore |
| | | **Sub-Total** | | **625831.84** | | **34333** |
| **Storage** | Insulated & vented Tank | | | | | |
| | pumping energy – covered under operational energy and emissions | | | | | |
| | | **Sub-Total** | | | | ignore |
| **Cooling** | mainly consists of pumping energy – covered under operational energy and emissions | | | | | |
| | | **Sub-Total** | | | | ignore |
| **Construction & Installation** | Concrete (hard surface for equipment) | 2$m^3$ (4800 kg) | 0.95 | 4560 | 263/$m^3$ | 526 |
| | Transport | 100 km | - | | 0.26/km | 26 |
| | | **Sub-Total** | | **4560** | | **552** |
| | | **TOTAL** | | **635754.418** | | **35258.6** |

Energy Pay Back Period (EPBP):

$$\text{EPBP} = \frac{\text{Energy consumed by power plant (kWh)}}{\text{Energy produced by power plant per year (kWh)}} = \frac{176598.45}{29700} = 5.95\ years$$

Energy Intensity:

$$\text{Energy Intesnity} = \frac{\text{Total Input Energy (kWh)}}{\text{Life Time Electricity Production (kWh)}} = \frac{176598.45}{594000} = 0.2973$$

Carbon Pay Back Period (CPBP):

$$\text{CPBP} = \frac{\text{Life Cycle } CO_2 \text{ emission}}{\text{Gross } CO_2 \text{ emission avoided per year}} \text{ x } 365 = \frac{35258.6}{(30450\text{-}304)} \text{ x } 365 = 426.9 \text{ days}$$

Carbon intensity:

$$CO_2 \text{ Intensity} = \frac{\text{Life Cycle } CO_2 \text{ emissions (g of } CO_2)}{\text{Life time electricity generation (kWh)}} = \frac{35258.6{*}1000}{594000} = 59.36 \text{ g/kWh}$$

## *7. Discussion and Conclusion*

It is evident from the negative NPV value (ZAR−126 389.64) that under the current scenario the 10 kW Low Temperature Solar Thermal Concept Power Plant is not an attractive investment option, economically. This is mainly due to the higher initial capital requirements, resulting largely from the higher costs of the IT10 power block (ZAR600 000), which is charged at research and development (R&D) rates, and the Solar Field (ZAR 1 260 000 solar collectors only). Under an assumed scenario, where the power block and the solar collectors are designed and produced locally (solar water heater collectors have been developed and tested at the UKZN over the past few years [10.11], [10.12]), their costs could drop to 50% or lower, the NPV realised becomes positive (ZAR+853 610.36); commercially available larger turbine generators in the Megawatt range cost from USD450 to USD 950 per kW [13]; a similarly rated 10kW natural gas generator supplied locally by Bundu Power, Johannesburg, South Africa is priced at ZAR67 932.60 [14].

The energy payback period (EPBP) was obtained as six years; this is considered comparable with other similar technologies. A typical solar power system is reported to payback after about four years, a photovoltaic system between one-and-half and three-and-half years, while a small wind turbine could take between fifteen to fifty years [15], [16].

Carbon payback period (CPBP) on the other hand was computed as 426.9 days (1.17 years); this figure too is comparable with what has been obtained by other researchers such as 2.21 years obtained for a solar water heater by Marimuthu C. and Kirubakaran V. [17], and carbon payback periods (excluding transport) obtained as 6.0, 2.2, and 1.9 years respectively for PV system, solar thermal-individual and solar thermal-community by Croxford Ben and Scott Kat [18].

The results obtained here are considered partial or conservative because the scrap and recycling values of the materials or components following decommissioning has not been taken into account; this would reduce the embodied energy and emissions.

The implications of these analyses do indicate that the low temperature solar thermal concept plant has potential to be a net clean energy producer both cost effectively and environmentally beneficially.

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