Feasibility Study of Concentrating Solar Power Plant for Sri Lanka

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Abstract – *Generating electricity from the energy of solar has minimum impact to the environment. The solar energy is a free, clean and renewable fuel which will never run out compare to fossil fuel that have been utilizing for electricity generation. The power plants which used the fossil fuel emit large quantities of carbon dioxide and other pollutants into the atmosphere. Even though in Sri Lanka, at present energy of solar is widely used to generate electricity using photovoltaic cells, due attention has not been paid to utilize the thermal energy of solar radiation to generate electricity. This paper presents the feasibility study of concentrating solar power plant in Sri Lanka. The country is closer to the equator and has the potential to generate electricity in bulk by utilizing thermal energy of solar radiation. Literature survey has been carried to identify the types of the plants available and climate condition required to have a concentrating power plant on a location. The availability of sufficient solar resources in the island and possible locations for the plant have been studied. Considering the potential locations to build CSP the best location was proposed. Plant type, capacity of the plant and required land area were also given. Finally, the cost per unit considering environmental benefit has been calculated*

Keywords: - *Concentrating solar power, Parabolic through type, Thermal storage, Technical frame conditions, Balance of plant*

Nomenclature
DNI –Direct Normal Irradiance (W/m$^{2)}$
C_p – Specific heat coefficient (J/kg. K)
T – Temperature (K)
P – Power (W)
S – Energy (J/S)
P – Density (kg/m^3 **)**
CSP – Concentrating Solar Power

1 INTRODUCTION

The use of renewable energy sources to generate electricity has been increasing significantly during last two decades. Technological advancement, cost reduction and less environmental impact are the main reasons for the use of renewable sources to generate electricity. Solar, wind, bio -mass and tidal wave become the main sources in generating

electricity. Solar photovoltaic and CSP are used to produce the electricity using solar energy. The use of solar photovoltaic is being used in many countries including Sri Lanka for generation of electrical energy.
CSP plants which utilize the thermal energy of the solar radiation to generate electricity has not been used widely till recent past. However, CSP has number of advantages such as generation of dispatchable energy, generation of electricity during the night and cloudy days. Therefore, the interest for constructing CSP plants in many countries where the sunlight is available has been growing. As a result, these plants are now being constructed in number of countries. Spain is one of the largest power producers from the CSP and number of large CSP plants are under construction in several countries including United States, India, China and North Africa.

The growth of electricity demand in Sri Lanka due to increase of population, access to the electricity and industrialization need to be met by connecting source of bulk power to the grid. This means new power plants need to be constructed to meet the future demand. At present hydro, coal, gas turbine and diesel power plants are used to generate electricity in bulk. Even though solar photovoltaic produces considerable amount of energy, still it is used to cover the power requirement of isolated consumers or used as back-up suppliers of energy. In contrary, CSP generate electricity in bulk by utilizing thermal energy of solar radiation. CSP requires large amount of direct sun light and best constructed in arid or semi-arid regions globally known as Sun Belt (Arora, 2013). Since Sri Lanka is located closer to the equator, the country does have a potential to construct CSP plant. However, introduction of a CSP to a Sri Lankan system to meet the demand has not been studied thoroughly yet. Therefore, the aim of this research work is to carry out a feasibility study to determine the capacity of a CSP in a suitable location of the country. At the end of the work the unit cost of the generation of CPS is presented. Since the CSP produces the electricity using thermal energy of the sun, the key factor to build up a CSP is the availability of solar radiation with required DIS. The climate conditions, land availability has been studied in order to meet the aim of this project. Since the CSP does not emit the pollutant to the atmosphere the unit cost has been calculated considering cost benefit due to non-emission of the pollutant to the environment.

2 REVIEW OF LITERATURE

Renewable energy sources are energy sources that do not last due to their use. Energy of solar, wind and tidal waves are fallen in to this category. Among these renewable energy sources, solar energy is the most useable source of renewable energy in the globe. The main types of solar energy systems in use today are photovoltaic and CSP. The main advantage of use of CSP technology against other renewable energy resources is that it has the capability of providing dispatchable energy using thermal energy storage system (Tamme, 2009).

It is expected that the sunniest countries should meet bulk peak and intermediate loads with the help of CSP by 2020 and base load by 2030 (Arora, 2013). It is also expected by 2050 CSP could produce 11.3 % of global electricity demand (Arora, 2013). The potential to build CSP in a country is assed based on availability of solar radiation, vulnerability of vegetation, proximity to transmission lines, availability of water bodies and flatness of the land.

Number of research work have been carried out across the globe to assess the potential of constructing CSP. It was revealed that Spain has the capacity to generate the electricity which is about 35 times higher than the electricity demand projected for the 2050. Similar research work in US done by Kirby et al. (2003), Karsteadt *et al.* (2005), Dahle *et al.* (2008). Charabi and Gastli (2010) reported that when using parabolic trough technology, a 100 MW power plant requires about 2.4 km^2 of land in Oman. In India it has been reported that about 35 – 50 MW capacity solar power plant can be set up on 1 km^2 land area. In addition to these more projects have being planned in Middle East, North African region, Australia, Latin America and South Africa (Ziuku, *et.al.*, 2009)

Solar photovoltaic converts the sun's energy to electrical energy using photovoltaic cells. As the suns light hit the solar panel, the solar radiation is converted into direct current electricity. Then the direct current is converted to alternating current using the inverters. Finally, alternating current distributed to the power network. This type of solar panels is connected to the grid at the consumers' locations and the excess of electricity over the power consumption of the individual consumer is exported to the grid during day time. Even though this feeds more power to the system, large number of inverters that are connected to the grid cause power quality issues due to the harmonics.

2.1 Operating principle of concentrating solar power plant

In CSP electricity is produced using heat energy of the sun. The mirrors and lenses are used to concentrate and focus the sunlight to a thermal receiver. The thermal receiver is similar to the boiler of conventional thermal power plant. The role of receiver is to receive the sun light and convert it to heat energy. The heat is absorbed and transported to the steam generator using thermal fluid. In most of the cases the synthetic oil is used as the thermal fluid. Then the heat is converted to the electricity in the steam generator where to this heat is transported. Block schematic diagram of a CPS is shown in figure 1. After receiving the heat to the steam generator, the operating principle is similar to the conventional thermal power plant. Since the sun light is available only part of the day, the part of the thermal energy produced is stored in thermal storage tanks to produce the electricity during the time when the sunlight is not available or not sufficient. For this purpose, two tanks with hot and cold thermal fluid are available. Unlike in solar photovoltaic cells the CPS cannot use the diffuse part of the solar radiation and direct radiation is required. The land that is required to produce the required amount of power using CSP is much larger when compare with the conventional thermal power plants. This may be the negative impact to the environment due to construction of CPS.

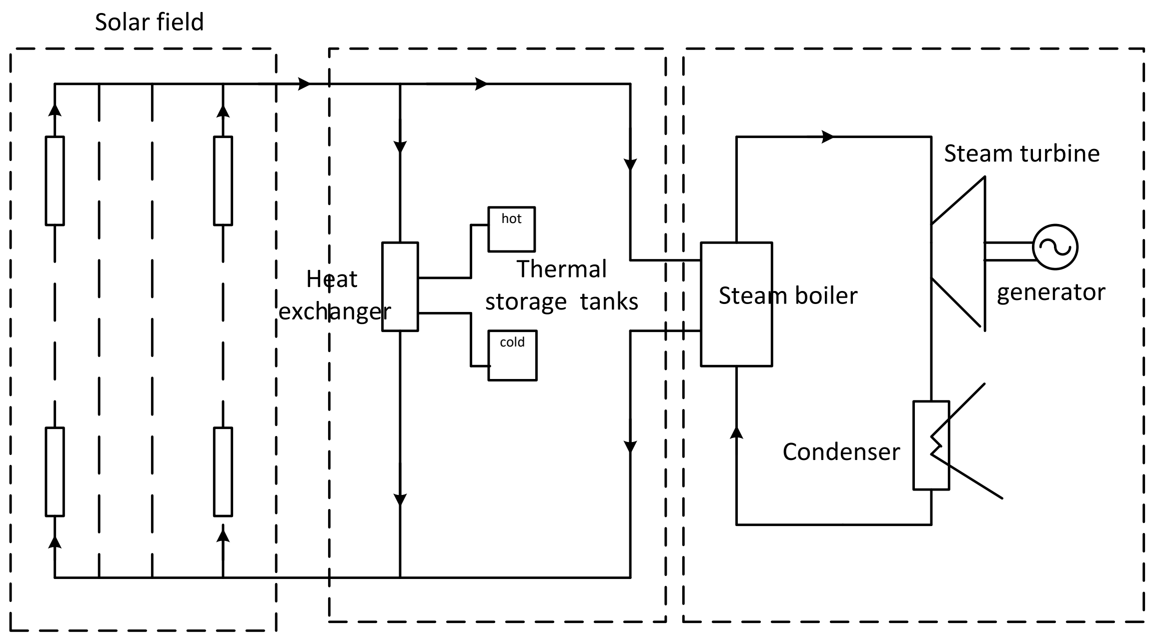

Figure 1: Diagram of a CSP plant

There are four different CSP systems: parabolic trough, power tower, parabolic dish and linear Fresnel reflector.

2.1.1 Direct normal irradiance (DNI)

The Direct Normal Irradiance is used to measure the solar energy that the concentrating solar power plant uses. This is the energy received on a surface tracked perpendicular to sun's ray. DNI provides the approximate capacity of a CSP. DNI is not a constant value and it varies throughout the day. Researches have shown that the minimum value of DNI to build concentrating solar power plant in a particular location is 2000 $kWh/m^2/year$ (www. setis.ec.europa.eu 2014).

2.1.2 Thermal energy storage

One of the major advantages of CSP systems is their ability to dispatch power beyond the day time sun hours by incorporating thermal storage system. The storage system retains heat efficiently so that it can be stored for a day before being converted in to electricity.

Presently, thermal energy options for parabolic through and power tower systems use molten salt as the storage medium in a two-tank heat system. Two tanks thermal energy system tends to be high efficiently as energy stored is recovered at nearly the same temperature.

2.2 Suitability of concentrating solar power plant for Sri Lanka

Sri Lanka is located within the equatorial belt, and therefore the energy of sun is available throughout the year. In the South Asian region, Sri Lanka together with India, Bangladesh and Pakistan comes under countries with semi-arid areas. The countries with semi-arid regions are considered as suitable locations for constructing CSP. Within the country there are enough lands available in the dry-zone to construct these types of plants. Many of these lands that are in dry zone are flat lands which is another requirement to have CSP. More ever, majority of these lands are not suitable for the cultivation or any other purpose and the values of them are minimum.

3 SITE SELECTION

3.1 Solar data collection

There are three sources for solar data collection: Typical Meteorological Year Data sets (TMY), surface meteorology and solar energy data sponsored by NASA and remotely collected data from meteorological department in Sri Lanka. Since the availability of sun light through the year is a key factor in designing CSP, the investigation of DNI was done for the dry zone of the country. Annual average DNI for selected locations of the country is shown in table 1. Researches have shown that the minimum value for DNI to construct CSP is 2000 kWh/m^2/year, which is equivalent to 5.45 kWh/m^2/day [Brayer and Knies 2009]. As per the data Mannar and Puthlam area are the suitable locations for constructing CSP.

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Table 1: Annual average DNI values in different areas

Area	Annual average DNI kWh/m^2/day
Hambanthota	5.37
Mannar	5.9
Puthlam	5.88
Jaffna	5.2
Trincomaly	4.93
Anuradhapura	4.53
Vavnia	4.54
Batticalo	4.36

3.2 Factors considered in Site selection

The CSP plants require more land areas for install large number of solar mirrors. Further, the slope of the land is also one of the key factors in deciding land for CSP. The accepted landscape is up-to 3% (Brayer and Knies 2009). In this work Google earth software was used to select the number of lands that satisfies this requirement and further analyses were done to check whether other conditions also were satisfied.

Water requirement is another most important criterion since CSP needs water for steam cycle, cooling and mirror washing. However, none of the above areas (Mannar and Puttlam) does not have source of the water to be used in CSP. At the meantime, both these areas are near to the sea and therefore desalinated water of the sea can be used for cooling purpose and mirror washing.

CSP need to be constructed in the proximity of power grid. The reason for this is to reduce the cost for transmission of energy produced by the CPS.
Access roads must be wider enough so that the large vehicles can be used for transportation of large number of parts of the solar field, heat exchangers, turbines generators etc.

3.3 Site location analysis

Considering all the factors given above Mannar area was selected as the most suitable location for constructing CSP. The area has the highest DNI value and the sufficient land is available for use. The water requirement for the plant is fulfilled by using the sea water. As the transmission lines of the grid are closer the transmission cost also can be minimized. According to the study the most suitable land is in the south-east region of the Mannar city. The site selected is 12 km away from the city (shown in figure 2) and the total area of the land is 900 x 1325 m^2 (117 ha). The cost of the land in this area is cheaper since it cannot be utilized for the agricultural purposes. Since this land is closer to the main road, the equipment of the CSP can be easily transported to the site.

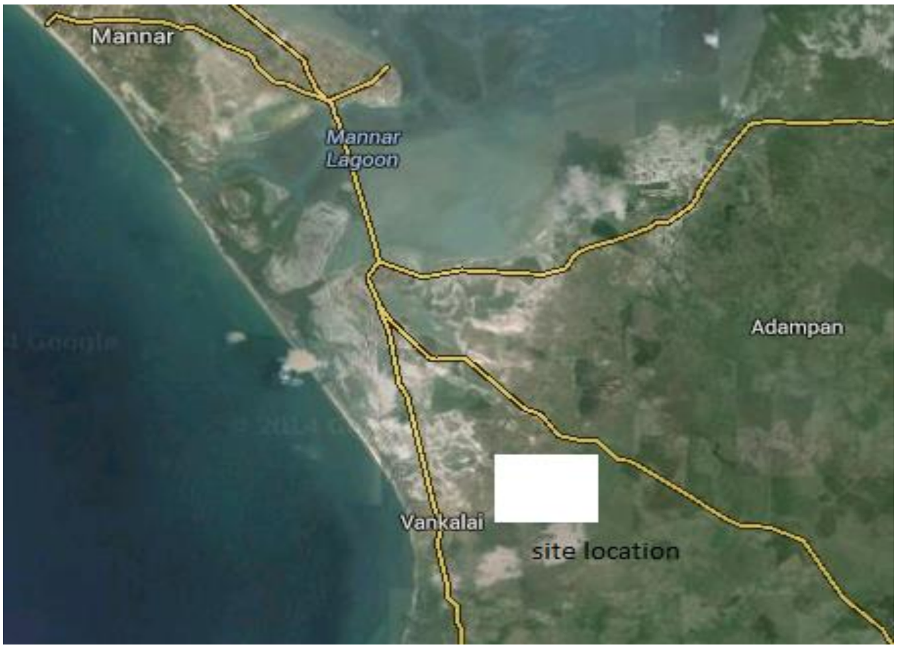

Figure 2: Site location

3.4 Average solar data in the site

The Surface Meteorology and Solar Energy Center provides monthly averaged data for last 22 years. According to the longitude and latitudes of the selected location monthly averaged DNI data was collected and shown in table 2.

Table 2: Monthly Averaged Direct Normal Radiation in the Mannar

Month	Average DNI (kWh/m²/day)
January	5.89
February	7.13
March	7.76
April	6.51
May	5.97
June	5.68
July	5.89
August	5.83
September	6.01
October	5.07
November	4.36
December	4.76
Annual average	**5.9**

4 POWER PLANT DESIGN

4.1 Modeling of solar system

Solar system modeling is the major task in CSP power plant design. Therefore, many of the solar system designers use software applications for their system modeling. The System Advisory Model (SAM) is the software which represents the cost and performance of renewable energy projects using computer models.

The selection of the solar field and suitable tracking system is important in designing CSP . In this work it is proposed to use LS-2 solar field since from the economical point of view it is one of the most suitable one for this purpose. The length and width of it are more economically suitable. .

4.2 Power plant layout

According to the land area of the site the total solar field and no of collectors which can be install in the site is calculated. Area for power block and storage also calculated.

Calculations are done according to the details of existing power plant.

Total land area = 900 m×1325m =1170000 m^2

Including the power block and optimal storage the power plant land area is selected as about 4.7 times the total solar field area (Jayakumar, P. 2009).

Total area for solar field = 1170000/4.7
= 250000 m^2

$$\text{No. of solar collectors for plant} = \frac{\text{total area for solar field}}{\text{collector mirror area(LS}-2)} = \frac{250000}{235} = 1064 \quad (4.1)$$

if the DNI received during 12 hours per day, the average solar insulation is calculated

$$\text{Average solar insulation} = \frac{5.9\times3600}{12\times3600} = 0.492 \text{ kW/m}^2 \quad (4.2)$$

Solar insulation in one collector = collector mirror area × average solar insulation. (4.3)
= 235 m^2 ×0.492 kW/m^2
= 115.62 kW

Considering that the collector field efficiency is 0.81 (www.nrel.gov,2015), receiver input was calculated
Receiver input = collector efficiency × solar insulation. (4.4)
= 0.81 × 115.62 kW
= 93.65 kW

Considering that the receiver efficiency is 0.88 (Arora, 2013)
Receiver output = receiver efficiency × Receiver input (4.5)
= 0.88 × 93.65 kW
= 82.41 kW
This means that thermal fluid absorbed power in one collector loop equal to the 82.41 kW.
Thermal fluid mass flow rate (m)through the receiver is given by

$$\mathbf{m = \rho\ AV} \quad (4.6)$$

Where
- ρ = 1680kg/m^3 for molten salt
- A = Receiver cross section area 0.00384m^2 (receiver diameter is 0.07m)
- V = fluid velocity set to 1.2 m/s

This gives the value of m as 7.74 kg/s

If energy absorbed by heat transfer fluid is **Q**, heat transfer fluid temperature increase in one solar collector is Δt and thermal fluid specific heat $\mathbf{c_p}$ is 1520 J/kg.K the temperature increase can be calculated formula given in (4.7)

$$\mathbf{Q = m\ c_p\ \Delta t} \quad (4.7)$$

This gives the value of Δ**t** as 7 K (or 7 ^{0}C)

Normally, temperature difference in hot fluid and cold is 110 ^{0}C (cold fluid temperature is 280 ^{0}C and hot fluid temperature is 390 ^{0}C). To keep this temperature difference the required number of solar collectors for one loop can be calculated.

Considering that the **Δt** is 7
No of solar collectors per loop = 110 /7 = 15.7
Required number of loops: 16

No. of solar collector loops = 1064 / 16
= 66 (4.8)
This means, 104 collectors having 66 collector loops will be installed in the area.

4.3 Plant Capacity Calculation

Using the selected site details plant capacity and storage power are calculated. All the efficiency values stated are obtained from "assessment of parabolic trough and power tower solar technology cost and performance forecasts" by Sergeant and Lundy LLC consulting group, Chicago for NREL in 2003 (www.nrel.gov ,2015).

Annual average DNI at site = 5.9 kWh/m²/day

$$\text{Total solar field area} = \frac{\text{Tolal solar insulation}}{\text{avarage insulation}} \quad (4.9)$$

Total solar insulation = Total solar field area × average insulation (4.10)
= 250000 m² ×0.492 kW/m²
= 123 MW

$$\text{collector field efficiency} = \frac{\text{Total collector output}}{\text{total solar insulation}} \quad (4.11)$$

Since the total collector output is equivalent to the total receiver input, the receiver input can be calculated

Total receiver input = collector field efficiency × total solar insulation (4.12)
= 0.81 × 123 MW
= 99.6 MW

Considering that the collector field efficiency is 0.81 (Jayakumar, 2009)

$$\text{receiver efficiency} = \frac{\text{total receiver output}}{\text{total receiver input}} \quad (4.13)$$

Considering that the Receiver efficiency is 0.88 (www.greenpeace.org, 2009) the output of the receiver can be found:

Total receiver output = receiver efficiency × total receiver input
= 0.88 × 99.6 MW
= 87.67 MW

This is the electrical power generated including the power that is stored to utilize when the sun light is not available

Next step is to calculate the amount of power that is stored. Before determining this value, it is required to calculate solar multiple. Solar multiple is the ratio of the receiver design thermal output to the power block's design thermal input. The values shall be determined by the hourly solar resource pattern.
At the site solar multiple is taken as 1.5 (according to software value 1.53).
Let the power to store is **S**.
Then,
Power to direct electricity generation = total receiver output – power to store
= 87.67 – **S**
Power to store = (solar multiple – 1) × power to direct electricity generation.
S = (1.5 -1) × (87.67-**S**)
S = 29.2 MW

Power to store is 29.2 MW
Then,
Power that goes for direct electricity generation = (87.67 -29.2) = 58.5 MW

Thermal to electrical efficiency

Net electrical power output from the plant was calculated considering the thermal efficiency of the turbine as 33%

Electrical power output = thermal to electrical efficiency × thermal power input
= 0.333 × 58.5 MW
= 19.5 MW.
Similarly, Electrical power output by storage power = 0.333 × 29.2 MW (4.14)
= 9.7MW

Plant capacity 19.5/0.9 = 21.6 MW

For 8 hours, storage energy = 9.7 MW ×8 hr
= 77.6 MWh
No of hours plant can work full load by store energy = $\frac{77.6 \text{ Mwh}}{19.5}$ = 4 hrs.

4.4 Power block

CSP requires steam turbines which are optimized for their complex and challenging cycle condition and further CSP turbine requires large number of start-up and fast daily start up capability. When focusing on annual power production, the short start up time of the turbine adds great benefits to the CSP plant.
Steam Turbine:
Considering the manufacturer data (www.siemens.com 2012), the selected turbine has following specifications:HP turbine: 100 bar , 371 °C; LP turbine: 10 bar, 371 °

Generator:

Since the output of the plant is 19.5 MW, it is proposed to install 25 MW, 11 kV generator unit for the plant. It is also proposing to install the 30 MVA, 11 kV/33 kV transformer to step up the voltage and connect to the existing 33 kV distribution line

As it was mentioned the water requirement is fulfilled by desalination of sea water. Per minute water requirement to generate 22 MW in the thermal power plant is around 66 m^3. This requires construction of desalination plant which provides demineralized water and service water. The demineralized water is for steam generator and the service water is for mirror washing and other water requirement of the plant such as firefighting systems.

4.5 Cost calculation

The cost calculation was carried out to determine the specific life cycle cost. The major cost involved in construction and operation of the plant are

(a)Direct cost	$ 82,295,000.00
(b)Indirect cost	$ 9,764,950.00
(c)Total installed cost (a+b)	$ 92,059,950.00
(d) Operation & Maintenance cost	$ 1,010,299.00
(e)Present value of O & M cost (dx9.427)	$ 9,524,095.75
Total present value of cost (c+e)	$ 101,584,045.75

The direct cost includes cost for site preparation, solar field, thermal storage power plant and cost for balance plant. The solar filed cost including cost for civil work, supporting structure, receiver, mirror and other equipment is \$250 per m². Indirect cost includes the cost for engineering, procurement & construction and land cost.

The present value factor (Nate, 2014) was calculated considering the present worth factor (r) as 10% and plant life time (n) as 30 years:

$$\text{Present value factor} = \frac{(1+r)^n-1}{r(1+r)^n} \tag{4.15}$$

$$= \frac{(1+0.1)^{30}-1}{0.1(1+0.1)^{30}} = 9.427$$

Considering that the plant availability factor is 94% and the plant operates in full capacity during 12 hours per day, annual plant output becomes 57.85 GWh (19.5 × 12 × 263 × 0.94).

Capacity factor = 57.85 GWh /19.5 MW × 8760 h
= 33.8 %

The specific life cycle = (total present value of cost)/(present value of energy benefit)
= (\$ 101,584,045.75)/545.525GWh=\$0.18 /kW

Carbon credit price

When compare with the coal power plant the carbon dioxide (CO_2) emission of CPS is zero. The benefit of the CPS due non- emission of CO_2 was calculated.

In a coal power plant CO_2 emission per kWh is 0.944 kg. The total emission of CO_2 in coal power plant with similar capacity would be 54610.4 ton per annum (=0.944 kg/kWh x 57.85 GWh). This is 54610.4 carbon credits (One ton of carbon is one credit). Since the present market value of carbon is \$21.25 per ton, total income from carbon credit is \$ 1,160,471.00 (=54610.4 × \$ 21.25)

Carbon credit price per kWh = \$ 1,160,471.00/ 57.85 GWh
= \$ 0.02 /kWh.

Specific life cycle cost with carbon credit cost saving = (\$ 0.18 - \$0.02) /kWh
= \$ 0.16 /kWh
= Rs. 20.80 /kWh.

Since one Carbon credit is ton of CO_2,

Available carbon credit	= 54610.4 Ton
Present market price per tonnage	= $ 21.25
Income from carbon credits	= $ 54610.4 × $ 21.25
	= $ 1,160,471.00

(Assumption: 1 US Dollar = 130 Rupee)

5 DISCUSSION

According to the economic analysis, the specific life cycle cost of CSP was $0.18 /kWh without carbon credit earning. This value is higher than unit cost of hydro and coal but lower than high cost diesel power generation. However, inclusion of CPS as one of the energy sources to Sri Lankan power system has a prospective due to following reasons:

Cost of solar thermal technology will continue to decrease with the rapid advancement of solar technology. Therefore, in future solar thermal electricity generation cost will be competitive with conversional sources such as coal.

According to the present scenario, in future base load of the system will be covered by coal and hydro while peak load demand will have meet by the diesel power plant. Unit cost of power generation by diesel is higher than concentrating solar power.

The third is the energy mix. It is said that concentrating solar power technology is dispatchable power generation technology which can work only in higher solar radiation areas. Hence CSP is most suitable for higher solar radiation area like Mannar. Then CSP can work instead of diesel power plant like a Chunnakam.

Finally, CSP will save the emission of carbon dioxide and other hazardous gases to environment.

6 CONCLUSION

It can be finally concluded that the parabolic through type solar thermal technology is technically feasible with available solar resources in Mannar area.
It also economically feasible with specific life cycle cost of $0.16 /kWh (with carbon credit saving) than diesel power plants considering with stored peak time generation.
Further it is environmental feasible technology by saving emission of carbon dioxide and other hazardous gases generated from coal and diesel.

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