KTH Industrial Engineering
and Management

Solar - Biomass hybrid system for process heat supply in medium scale hotels in Sri Lanka

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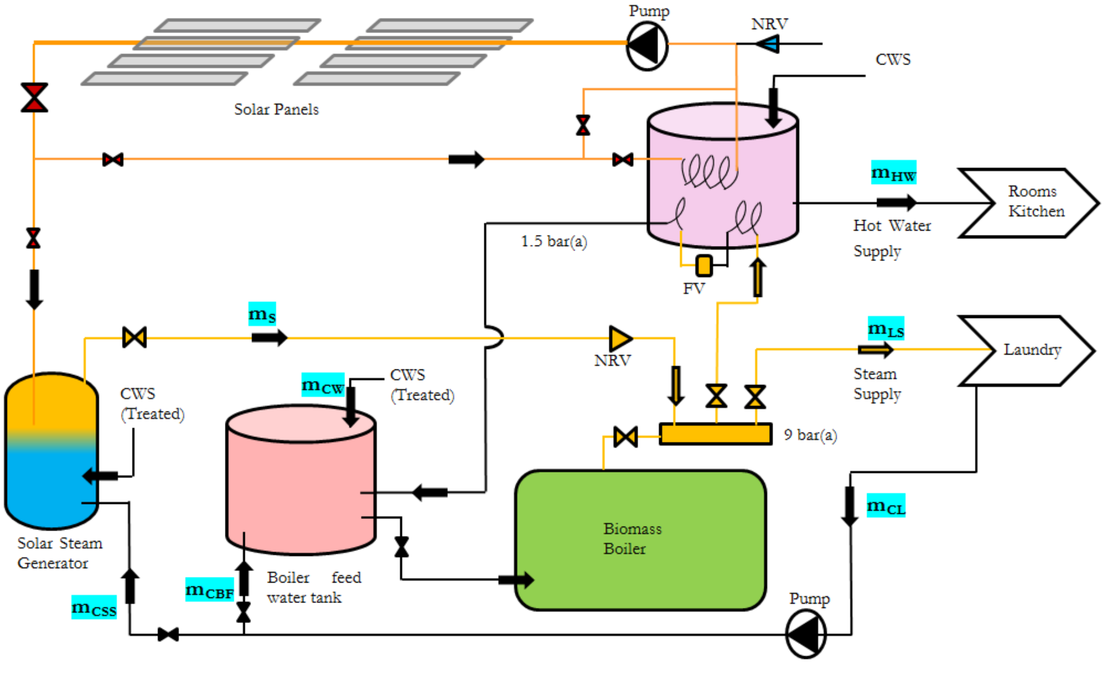

Master of Science Thesis

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KTH Industrial Engineering and Management	Master of Science Thesis EGI-2016-021MSC EKV1133 **Solar-Biomass hybrid system for process heat supply in medium scale hotels in Sri Lanka** Asela M.A.J. Abeywardana	
Approved 2016-06-23	Examiner Miroslav Petrov - KTH/ITM/EGI	Supervisors KTH – Miroslav Petrov OUSL – Dr. N.S. Senanayake Eng. Ruchira Abeyweera Eng. Asela Buddika Pathirathne
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Abstract

This study aimed at evaluating and demonstrating the feasibility of using Concentrated Solar Thermal technology combined with biomass energy technology as a hybrid renewable energy system to supply the process heat requirements in small scale industries in Sri Lanka. Particularly, the focus was to apply the concept to the expanding hotel industry, for covering the thermal energy demand of a medium scale hotel.

Solar modules utilize the rooftop area of the building to a valuable application. Linear Fresnel type of solar concentrator is selected considering the requirement of the application and the simplicity of fabrication and installation compared to other technologies. Subsequently, a wood-fired boiler is deployed as the steam generator as well as the balancing power source to recover the effects due to the seasonal variations in solar energy. Bioenergy, so far being the largest primary energy supply in the country, has a good potential for further growth in industrial applications like small hotels.

When a hotel with about 200-guests capacity and annual average occupancy of 65% is considered, the total annual CO_2 saving is accounted as 207 tons compared with an entirely fossil fuel (diesel) fired boiler system. The annual operational cost saving is around $ 40,000 and the simple payback period is within 3-4 years. The proposed hybrid system can generate additional 26 employment opportunities in the proximity of the site location area.

This solar-biomass hybrid concept mitigates the weaknesses associated with these renewable technologies when employed separately. The system has been designed in such a way that the total heat demand of hot water and process steam supply is managed by renewable energy alone. It is thus a self-sustainable, non-conventional, renewable energy system. This concept can be stretched to other critical medium temperature applications like for example absorption refrigeration. The system is applicable to many other industries in the country where space requirement is available, solar irradiance is rich and a solid biomass supply is assured.

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Nomenclature

A_M	Collector area of solar modules (m^2)
C_{IND}	Initial cost of diesel boiler system ($)
C_{ISB}	Initial cost of solar-biomass hybrid system ($)
C_{OMD}	Total operational cost of diesel boiler system ($)
C_{OMSB}	Total operational cost of solar-biomass hybrid system ($)
DNI_D	Daily Direct Normal Irradiation ($kWh/m^2/day$)
E_B	Energy supply by biomass boiler (J)
E_{CL}	Energy recovered in condensate after laundry (J)
E_{CW}	Energy content of cold water supply (J)
E_{HW}	Energy requirement to hot water supply (J)
E_{LS}	Energy required to laundry steam supply (J)
E_S	Energy supply by solar system (J)
E_T	Total energy requirement (J)
I_{SC}	Solar Constant (W/m^2)
ME_{CL}	Maximum energy recovered in condensate in laundry (J)
ME_{HW}	Maximum energy requirement to hot water supply (J)
ME_{LS}	Maximum energy required to laundry steam supply (J)
ME_S	Maximum total energy requirement (J)
m_{CL}	Mass of condensate water after laundry (kg)
m_{CW}	Mass of cold water supply to feed water tank (kg)
m_{HW}	Mass of hot water supply (kg)
m_{LS}	Mass of laundry steam supply (kg)
m_S	Mass of steam supply by solar steam generator (kg)
R_G	Occupancy ratio of the hotel (%)
S_F	Solar Fraction (%)
T_{HW}	Temperature of hot water supply (^0C)
T_{CS}	Temperature of cold water supply (^0C)
T_F	Temperature of boiler feed water tank (^0C)

δ	Declination Angle (Degree)
φ	Latitude (Degree)
ω	Hour angle (Degree)
θ_Z	Zenith angle (Degree)
γ_S	Azimuth angle (Degree)
θ_S	Altitude angle (Degree)
η_{Boiler}	Efficiency of boiler (%)
η_{Solar}	Overall efficiency of the Fresnel solar system (%)

Abbreviations

CEB	Ceylon Electricity Board
CSP	Concentrated Solar Power
CST	Concentrated Solar Thermal
CWS	Cold Water (makeup water) Supply
DNI	Direct Normal Irradiation
FV	Flash Vessel
GHI	Global Horizontal Irradiation
HHV	Higher Heating Value
LFC	Linear Fresnel Concentrator/collector
LFR	Linear Fresnel Reflector
LHV	Lower Heating Value
NRE	New/Non-Conventional Renewable Energy
NRV	Non Return Valve
O & M	Operation and Maintenance
ROI	Return On Investment
SEA	Sustainable Energy Authority, Sri Lanka
SLTDA	Sri Lanka Tourist Development Authority
SPP	Simple Payback Period

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1 INTRODUCTION

Promoting renewable energy in a country describes not only the development as a technology but also an expansion of ecological sustainability, competitiveness and security of energy supply. Due to these characteristics the industrialized countries have included renewable energy into their national agenda as a major strategy. This has become an indication for the development status in a nation.

The energy sector in Sri Lanka is experiencing severe strain due to the fluctuations of international oil prices as the country is very highly dependent on oil product based power generation in order to meet the rising energy demand. The rapid industrialization, value addition to raw products, broadening of service sectors such as tourism industry and also the rural electrification programs are key factors to this increase in demand. The Ceylon Electricity Board (CEB) is rapidly being drawn into more and more dependency on fossil fuel power generation, at very high cost.

Despite the above issues, Sri Lanka is blessed with renewable energy resources according to its geo-climatic settings. Some of them like hydro are widely used but still there are other areas like solar, wind and biomass to be explored and developed. "The Ministry of Power and Energy" encourages private sector to develop small non-conventional renewable energy projects as the best solution to overcome the looming energy crisis.

Concentrated Solar Power (CSP) technology is a good renewable energy concept to implement in Sri Lanka, as the country is situated near the equator and receives a sound solar irradiance. But the CSP technology has remained unpopular due to the various reasons. Flat-plate domestic type solar water heaters are popular but the total energy generated by this method is wasted during the low demand situations. Furthermore, the investments in this type of solar heaters are not fully utilized and it would not be feasible to apply these in real industrial applications.

1.1 Background

1.1.1 Tourist Industry in Sri Lanka

Sri Lanka is an island to be found with a unique geographical location in the Indian Ocean. It was known as the "Pearl of the Indian Ocean", and as referred to by most travel journalists it is called the "Jewel of Asia" or "Paradise on Earth". There is a great opportunity for promoting tourism within the region mainly due to Authenticity, Diversity and Compactness. The country has over 2,500 years of old traditional culture (authenticity) and offers a variety of climatic regions and different tourist attraction (diversity) within only 65,000 km^2 of land area (compactness). The tourism is currently blessed with peace and stable political situation in the country.

As notified by the Government Development Policy Framework, Sri Lanka is to be emerged as "Wonder of Asia" as it has the potential to be the next Asian economic miracle. The Ministry of Economic Development expects to attract visitors and to gradually increase the tourist arrivals to 2.5 Million by the year 2016 as described in the "Tourism Development Strategy".

The Sri Lanka Tourists Development Authority (SLTDA) was established to accomplish this target by facilitating and implementing the legal and administrative process to provide and to develop unique and quality tourism services and products, and to formulate and implement Tourism Development Guidelines by identifying and developing tourist-specific areas and services. The industry has experienced a moderate growth in 2011-2013 due to the limitations in facilities but expecting faster growth to achieve their target in 2016.

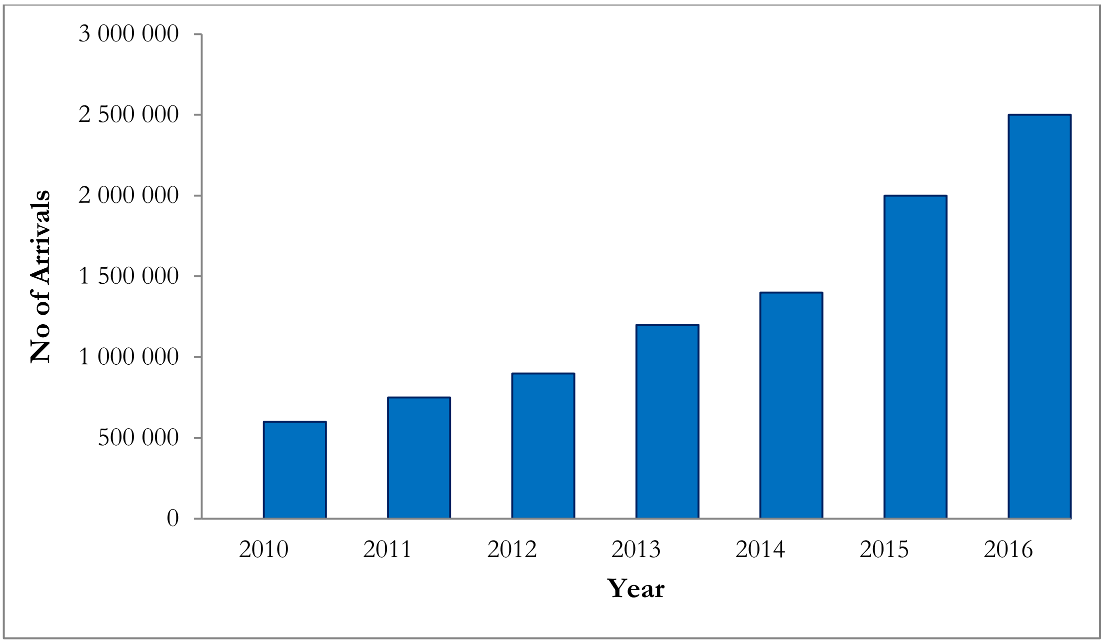


Figure 1: *Sri Lanka Tourists Targets (2010 – 2016)*
(Ministry of Economic Development, 2011)

1.1.2 Power consumption of the hotel industry

As described in the "Tourism Development Strategy", the SLTDA wish to transform Sri Lanka to be Asia's foremost destination. It has been revealed that there is a considerable growth in the tourism industry. The number of hotels registered that facilitate the tourism industry has been rapidly increasing during the last few years. Hence there is a significant growth of power consumption by this industry. Currently, the hotel industry has become such an important sector that it consumes more than 4% of the national electricity supply (Ceylon Chamber of Commerce, 2011).

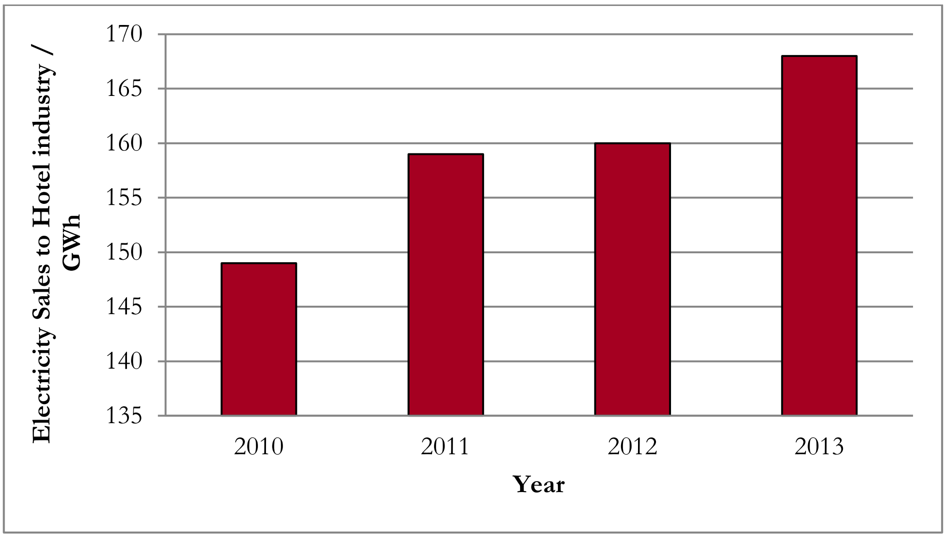


***Figure 2:** Variation of CEB electricity sales to the hotel industry*
(Ceylon Elecricity Board, 2011), **(Ceylon Electricity Board, 2012) (Ceylon Elecricity Board, 2013)**

The main electrical energy consuming sectors in the hotel industry are Air conditioning, Lighting, Kitchen and Laundry. *Figure 3* shows a typical electrical energy balance of a hotel in Sri Lanka.

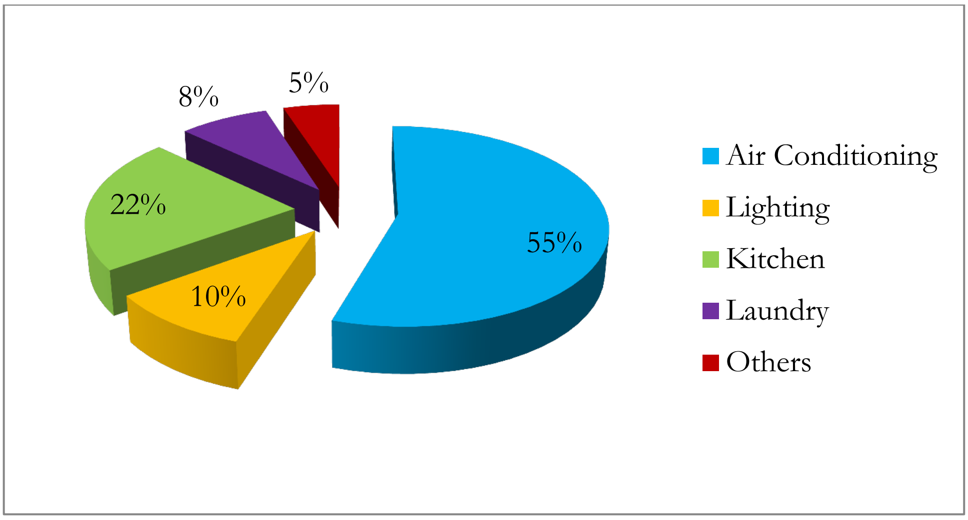


***Figure 3:** Typical Electrical Energy Balance of a hotel in Sri Lanka*
(Ceylon Chamber of Commerce, 2011)

Most of the energy analyses have been done by summarizing the electrical energy consumption as described above. Also, there are certain thermal energy applications like "kitchen ovens" that are operated by electrical supply. The major energy consuming sectors in a hotel appear to be different with the electrical energy consuming areas as discussed in Figure 3. There is a huge thermal energy requirement when the hotel is running an in-house laundry. The hot water requirement is also a high energy consuming area. So the thermal energy requirement is a vital factor to deal with when considering the energy saving potential. *Table 1* shows the energy consumption data for a set of leading 5-star hotels in Sri Lanka having an in-house laundry.

Table 1: *Energy consumption data for a set of leading 5-star hotels in Sri Lanka*
(Ceylon Chamber of Commerce, 2011)

Hotel #	Average Daily electricity consumption/ (kWh/day)	Average Daily Steam Usage / (kg/day)	Steam Pressure/ bar
1	20,553	13,141	7
2	25,504	29,315	6.2
3	8,079	5,154	10
4	9,604	6,648	10.4
5	24,700	23,730	7.5
6	16,560	11,672	7.5
7	16,834	10,713	7
8	10,240	5,747	7.5
9	37,397	23,871	7.3

The electricity consumption is given in "kWh" in the available data listed in *Table 1*. The thermal energy in the steam demand can also be converted to "kWh" (assume latent heat and the 30% of the condensate energy used) and the relevant comparison can be obtained as shown in ***Table 2*** below. Then it is revealed that the thermal energy requirement satisfied by steam generation in a five-star class hotel in Sri Lanka is around 30% of the total energy requirement. Thus the hot water and steam requirements are vital areas to deal with in case of energy sustainability goals.

Table 2: *Comparison of electrical energy and thermal energy consumption, reworked data from Table 1*

Hotel #	Average Daily Electricity consumption/ (kWh/day)	Average Daily thermal energy (Steam) Usage / (kWh/day)
1	20,553	8,263
2	25,504	18,508
3	8,079	3,199
4	9,604	4,119
5	24,700	14,888
6	16,560	7,323
7	16,834	6,736
8	10,240	3,606
9	37,397	14,988
Total	**169,471**	**81,630**

Other than the concerns about the global warming, climatic change and the growing global energy crisis, the sustainability applications in the hotel industry has become a considerable issue as well as getting additional benefits with extra tourists attraction through "Greening" standards. Thus the "Greening of Sri Lankan hotels" is continually being implemented with the appropriate energy, water and waste management programs through better environmental practices. The renewable energy can play a major role in achieving sustainability with the help of improved energy management and conservation strategies.

1.2 Objective

The objective of the study was to demonstrate the feasibility of utilizing renewable energy sources by minimizing the weaknesses associated with such technologies to meet some of the energy requirement in hotel industry.

Particularly, the study was focused on the following major aspects:

- To evaluate the feasibility of using concentrated solar thermal technology in the hotel industry for meeting process heat requirements; and
- To model a concentrated solar thermal and biomass-fired boiler hybrid system to meet the steam and hot water requirement of a typical medium scale hotel.

1.3 Methodology

- The project starts with a literature survey which is continued throughout the project to get a thorough knowledge and to get updated the available technology on the subject. The technological findings over this literature survey are discussed in initial chapters which is useful in the analysis process in the following chapters;

- The energy survey related to the hotel industry was carried out to assess the system requirement correctly and to identify the practical issues. Information gathered through surveys was analyzed in order to provide foundation for model design and for design proceedings in comparison with the available standards and design practices;

- Data surveys on the solar potential and on the biomass potential in Sri Lanka were carried out through the information available with the sources and publications of government regulatory bodies, research publications from relevant organizations and with information available from on-going projects;

- Designing of a proper hybrid system that meets the requirement of the application unit (hotel) was done based on the information gathered during this study and further possibilities of optimizing the system was considered by varying the solar-biomass combination (i.e., varying the weight of the energy contribution to the application by solar energy and by bioenergy).

- A computer program specific to this system was developed in the process of this optimization and the improvements of the system parameters. Repeated calculations by varying the input parameters of this solar-biomass hybrid combination can be done by using this specific program to evaluate the results and limitations for finding better alternatives.

- Results of the optimization process were evaluated against the technical and economic considerations to find out the best options. Financial feasibility was investigated with basic indicators in comparison with a fossil fuel system.

- Environmental and social benefits of this hybrid renewable application were assessed over the weaknesses associated with the fossil fuel system.

2 LITERATURE SURVEY

2.1 SOLAR ENERGY

2.1.1 Solar Radiation

Solar energy that arrives on the Earth as a form of radiation is an energy emitted by greatly exited atoms of the Sun originating in the continuous reaction known as nuclear fusion. The prevailing reaction directly converts the mass into energy by combining two Hydrogen atoms into one Helium atom. The sun fuses 620 metric tons of Hydrogen in each second and releases massive amount of energy at a rate of around 3.85×10^{26} W.

The sun holds these hot gases by its gravitational pull having a diameter of 1.39×10^{9} m. The Earth while spinning on its own axis having a diameter of 1.27×10^{7} m is travelling around the Sun in an elliptic orbit. The mean distance between Sun and Earth is 1.5×10^{11} m. It subtends at an angle of only 32' (thirty two minutes) on the Earth's surface due to this distance (Spelling, 2011). Therefore the Earth receives almost parallel beam radiation from the Sun.

The rate at which this energy is received on a unit area perpendicular to the direction of propagation of the radiation at the mean distance of the Earth from the Sun is called the "Solar Constant" (I_{SC}). The standard value for this constant is agreed as 1,367 W/m^2 but it shows ±3% variation over the complete traverse of the Earth around the Sun.

2.1.1.1 Atmospheric Condition

Despite the fact that the solar energy should be reached as per the solar constant I_{SC}, there will be a huge variation to the actual energy received on the earth's surface as it has to pass through the earth's atmosphere. This is mainly due to the reflection, absorption and scattering of solar radiation by the particulate and the gaseous elements in the atmosphere. Then there will be a huge loss as a result of this atmospheric absorption and reflection. Even on a clear day around 30% of the energy is absorbed, resulting in a peak flux at the surface of around 1,000 W/m^2.

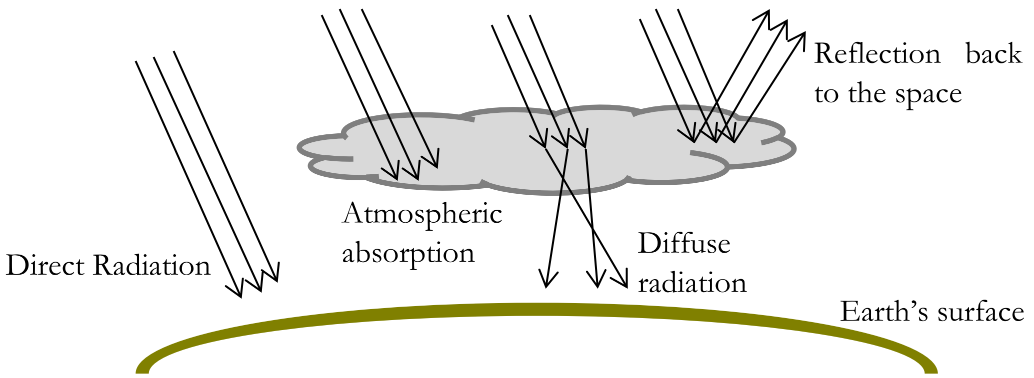


Figure 4: *Atmospheric effects on the solar radiation*

Direct/Beam Radiation – Solar radiation received at the Earth's surface without change in the direction is called beam or direct radiation.

Diffuse radiation – Solar radiation received at the Earth's surface from all the directions after being scattered in the atmosphere is called diffuse radiation.

Global/Total radiation – The sum of the beam and diffuse radiation is called total or global radiation.

2.1.1.2 Solar Radiation Geometry

The most prominent variation of solar radiation on a particular location is a result of the inclination of the Earth's axis of rotation to the Earth's orbital plane. This natural phenomena measured as an angular distance called "Declination angle (δ)" is varied from -23.5^0 to +23.5^0 over a complete orbit around the sun (throughout the year). For example, δ = +23.5^0 on 21st June, δ = 0^0 on 21st March and 21st September, δ = -23.5^0 on 21st December. The declination angle can be given by,

$$\boldsymbol{\delta} \textbf{ (in degrees)} = \mathbf{23.45 \sin} \left[(\mathbf{360/365}) \boldsymbol{X} \, (\mathbf{284} + \boldsymbol{n}) \right] \qquad \text{(Mukherjee D., 2005)}$$

Where, n is the calendar day of the year, (e.g. for June 20 in 2011, n = 31+28+30+31+20 = 171).

This inclination is the cause for all the seasonal variations in both hemispheres while the level of this variation is depending on the "latitude (φ)" of the location on Earth. Every other factor in effect to the intensity of the solar radiation is determined by the Declination angle (δ) and the latitude of the location (φ) together with the atmospheric condition as described in section 2.1.1.1. The length of a the day time in a given location on a given day can be obtained by,

$$\mathbf{N} = {}^{\mathbf{24}}\!/_{\boldsymbol{\pi}} \; \mathbf{cos^{-1}} \left[-\mathbf{tan} \left(\boldsymbol{\pi} \, \frac{\boldsymbol{\varphi}}{\mathbf{180}} \right) \mathbf{tan}\, \boldsymbol{\delta} \right] \qquad \text{(Spelling, 2011)}$$

Where, **N** is the day length given in hours

Certain parameters have been introduced to estimate the intensity of incident solar radiation on a given time in a day for a given day of the year for a given location.

Hour angle (ω) is the angle through which the earth has rotated since noon. It is equivalent to 15^0 per hour and will be varied from -180^0 to +180^0. The Hour angle is given by,

$$\boldsymbol{\omega} = \frac{\boldsymbol{\pi}}{\mathbf{2}} \, (\boldsymbol{t_s} - \mathbf{12}) \qquad \text{(Spelling, 2011)}$$

Hour angle is measured from the noon based on the local solar time t_s where, t_s is defined 12.00 as the moment when the Sun is exactly due south at the local position.

Zenith Angle $(\boldsymbol{\theta_Z})$ is the angle between the Sun's rays and a line perpendicular to the horizontal plane through the observation point. The Zenith Angle is given by,

$$\boldsymbol{\theta_Z} = \mathbf{cos^{-1}} (\mathbf{cos}\, \boldsymbol{\varphi}\, \mathbf{cos}\, \boldsymbol{\delta}\, \mathbf{cos}\, \boldsymbol{\omega} + \mathbf{sin}\, \boldsymbol{\varphi}\, \mathbf{sin}\, \boldsymbol{\omega}) \qquad \text{(Spelling, 2011)}$$

Azimuth angle $(\boldsymbol{\gamma_S})$ is the angle from north to the horizontal projection of Sun's rays at the observation point.

$$\boldsymbol{\gamma_S} = \mathbf{sin}(\boldsymbol{\omega}) \left| \mathbf{cos^{-1}} \left[\frac{\mathbf{cos}\, \boldsymbol{\theta_Z}\, \mathbf{sin}\, \boldsymbol{\varphi} - \mathbf{sin}\, \boldsymbol{\delta}}{\mathbf{sin}\, \boldsymbol{\theta_Z}\, \mathbf{cos}\, \boldsymbol{\varphi}} \right] \right| \qquad \text{(Spelling, 2011)}$$

Altitude angle $\boldsymbol{\theta_S}$ is the vertical angle between the projection of Sun's rays on the horizontal plane and the direction of Sun's rays passing through the observation point.

$$\boldsymbol{\theta_S} = \boldsymbol{\theta_Z} - (\boldsymbol{\pi}/\mathbf{2}) \qquad \text{(Spelling, 2011)}$$

2.1.2 Solar Energy Technology

Solar power has been a primary source of energy to the mankind and there are some examples that the solar technology has been used by humans thousand years ago. This technology could be found in simple applications like "drying crops" and in advance applications like passive solar architecture used in ancient Greece buildings. Today the technology has developed to such an advanced level that it can directly produce electrical energy by using solar energy in devices called "Photovoltaic Cells".

Passive solar technology refers to the technology that merely collects and uses the thermal effect of solar energy in buildings. "Passive Solar Building" architecture that optimizes the energy consumption by the design is a great example of this type of technology.

Active Solar technology refers to harnessing solar energy by maximizing the effectiveness, storing or converting to any other forms of energy and using it with effective methods. Photovoltaic cells and solar thermal technologies are the two main groups of this application.

2.1.2.1 Solar Thermal Power

A solar thermal system is an arrangement that harnesses the solar energy and converts it to a useful form of heat energy. Generally, this process by concentrating the solar radiation produces hot water, steam or hot air which can then be used directly the heat requirements or it can be used to generate electricity by using conventional power cycles. Solar energy is a relatively low density energy that needs to be concentrated to make use of it. Solar thermal collector is the device that collects this energy and transfers it to the device called absorber where the working fluid is in contact to absorb as heat energy.

Depending on the geometry, there are two basic types of solar collectors that can be found as "concentrating" and "non-concentrating". In the non-concentrating types, there is no optical concentration involved where the collector area is same as the absorber area. Flat plate collector is the best example for this type used commonly in domestic solar water heating and space heating systems. These collectors can heat water or air only up to 80^0C.

Concentration method where the optical concentration is involved by the geometry of the reflector allows a high density of energy to be absorbed for a given absorber area. Thus higher temperatures can be achieved with this denser concentrated energy. Due to the reduced absorber area, the radiation loss is minimized and relatively higher thermal efficiency can also be attained.
Most of the applications like industrial process heat, refrigeration or air conditioning by absorption refrigeration cycle and power generation by steam or gas cycle are in the range of 80^0C to 250^0C whereas the concentrated solar technology can be used.

As the radiation travels through straight lines, it can be explained with a simple graphical clarification that only the parallel radiation can be focused to a point. The diffused part of the radiation is not useful for this purpose and only the beam radiation or the direct radiation is considered.

The solar concentrator can be of **line focusing** type or of **point focusing** type. Line focusing is a two dimensional concentration method where the maximum theoretical concentration ratio up to 212 can be achieved. Point focusing is a three dimensional concentration method where the maximum theoretical concentration ratio is as high as 45,000. The real practically achievable optical ratios are different from these theoretical values. Line focusing systems can only produce up to 100 concentration ratios and operate at maximum of 450^0C. Point focusing can produce the concentration ratios above 1000 and the temperatures as high as 2000^0C (Spelling, 2011).

"Parabolic Trough" and "Linear Fresnel" concentrators are common examples for the line focusing systems whereas "Parabolic Dish" and "Heliostat Field" concentrators are popular in point focusing systems. The point focusing, as it is being a three dimensional behavior requires a two-axis tracking device on the collector to maintain the beam focus. Relatively high capital investment is required for point focusing systems which are commonly used in medium to high temperature applications like power generation and material testing. Line focusing requires single-axis tracking on the collector where the capital investment is relatively low. Line focusing systems are used for the medium temperature applications like process heat requirements and also in the power generation.

2.1.2.2 Linear Fresnel Collector (LFC)

Linear Fresnel Collector/Reflector by geometry is a line focusing system which is most appropriate for the medium range temperature applications like process heat. The other line focusing concentrators like Parabolic Line focusing system or "Trough" system can satisfy these requirements better. However, this particular project promotes the Fresnel type of solar thermal technology considering the lower capital investment and the simplicity of fabrication and installation if compared to other CSP technologies. The Fresnel technology uses series of long flat mirrors reflecting the beam radiation to the line of fixed receiver. Every single mirror line is equipped with individual tracking drivers and rotates along its own axis. For a given instance they should be at different angles to point the receiver. All these rotating axes are parallel with each other while the line of focus where the receiver is placed is also parallel with these rotating axes.

Figure 5: *Fresnel Collector Solar Field*
(CSP16)

For the medium temperature range applications, the "trough" type collectors are also suitable especially in view of their greater optical efficiency. But there are some advantages with the Linear Fresnel Collector over the trough type collector, as follows:

- Linear Fresnel Collector uses flat mirrors which are commonly available.
- Supporting structure is lighter than trough type making it more suitable for some rooftop installations.
- Individual tracking drivers for each mirror reflector line make the driving system lighter and simpler.
- Higher land use efficiency than any other CSP technology.
- Higher collector area per absorber can be achieved. Cost is reduced as the absorber is a costly component if compared to the others.
- Suitable for direct steam generation due to the fixed receiver.
- Cheaper and simpler technology, easier fabrication and installation.
- This moderate technology should be more suitable for implementation in countries where more advanced technologies are not available or require higher investments or more demanding operation and maintenance procedures.

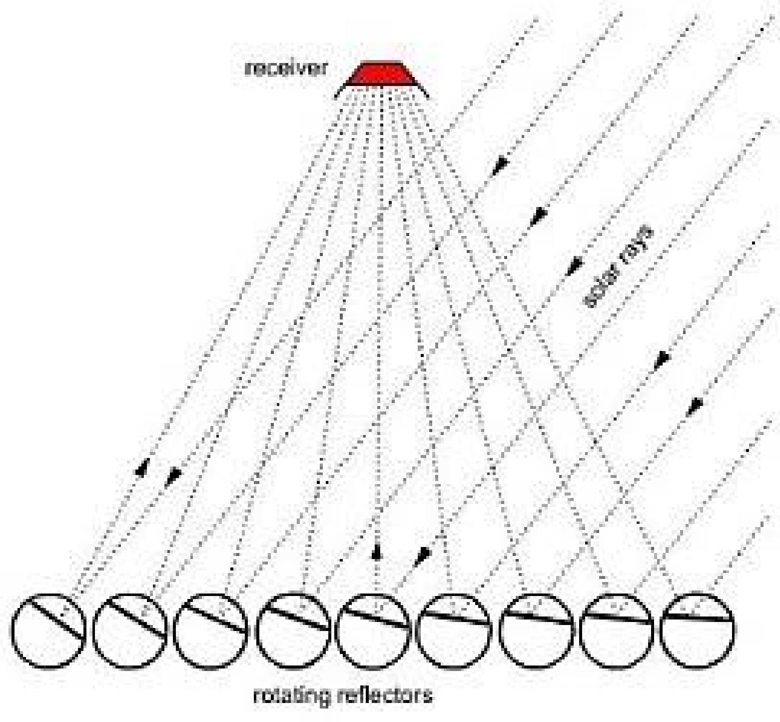


Figure 6: *Geometrical view of Linear Fresnel Collector*
(htt16)

2.1.2.2.1 Secondary receiver

The receiver in the LFC is different than in the trough type collectors. Due to the parabolic geometry, a sharp focal point or line can be achieved in the trough type CSP technology but in the LFC the shape of the collector is basically a flat profile that results from narrowed parallel radiation directed towards the receiver. In order to minimize this optical inaccuracy and to catch this parallel radiation, a secondary concentrator is introduced. Then the concentration ratio can be increased and larger absorber tubes can be avoided resulting in minimum radiation losses in the absorber. Secondary concentrator can again be a parabolic shape but the simple type concentrator as shown in *Figure 7* is also available with the advantages of cheap and easy fabrication. This secondary concentrator further acts as a thermal insulator to the absorber. Then the much simple and cheaper absorber tubes without vacuum insulation can be used in LFC systems. Being this simple gives an additional advantage of this technology to be feasible for the small and medium scale applications.

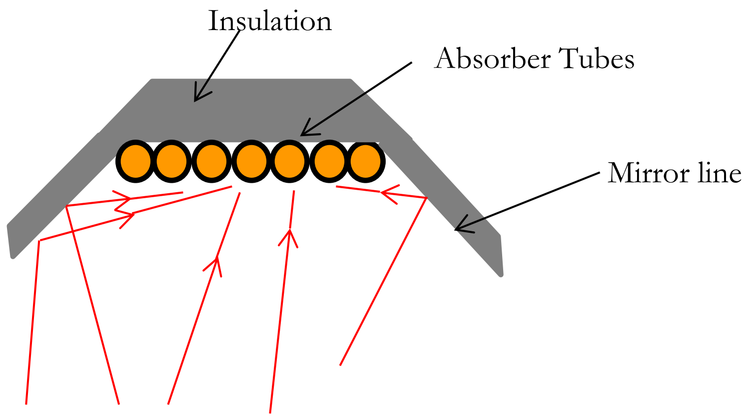


Figure 7: *Geometry of a simple secondary receiver*

2.1.2.2.2 Tracking System

Linear Fresnel technology is a line focusing system and it uses a single axis tracking device.

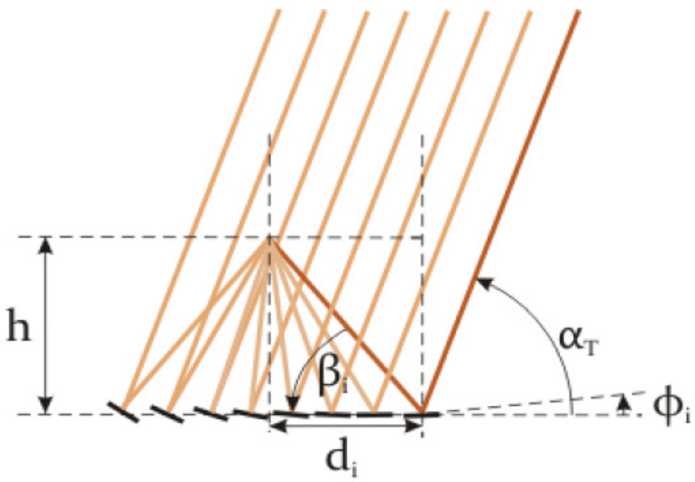


Figure 8: *Mirror tilt angle and its determinants*

(Gunther, 2012)

For a given incidence angle each mirror line has different angles to track the sun radiation as illustrated by *Error! Reference source not found.*. This modified tilt angle can be given as φi,

$$\varphi i = \frac{\alpha_T - \beta_i}{2}$$

Where, α_T is the transversal solar altitude angle,

β_i is determined by $\beta_i = \tan^{-1}\frac{h}{d_i}$

Where, the height of the absorber over the mirrors plane (h) and the distance to the respective mirror row from the projected axis of the absorber to the mirror plane (d_i).

Then, the tracking tilt angle can be obtained,

$$\varphi i = \frac{\alpha_T - \tan^{-1}\frac{h}{d_i}}{2}$$

The deviation of this angle with respect to time or the variation with respect to α_T can be obtained as,

$$\frac{d\varphi i}{dt} = \frac{1}{2} \cdot \frac{d\alpha_T}{dt}$$

(Gunther, 2012)

An important characteristic for this tracking angle is obtained where this angle variation is only dependent on the Sun's movement (α_T) and it is independent of mirror position (h and d_i). For a given instance, even though the tracking angles are different, they follow the same angular variation with the Sun's apparent movement. This reveals that the individual tracking drivers can be controlled by a central tracking system. There is a certain inaccuracy involved with this central drive system but it is economically feasible as less equipment drive gears are deployed.

2.1.2.2.3 Efficiency

The power output $\dot{Q}_t$ for a specific area "A" of the thermal collector of LFC is given as,

$$\frac{\dot{Q}_t}{A} = \left(\dot{Q}_{inc} - \dot{Q}_{loss}\right)$$ (Heimsath A, 2013)

Where, $\dot{Q}_{inc}$ is total absorbed power and $\dot{Q}_{loss}$ is thermal power loss. The total absorbed power $\dot{Q}_{inc}$ can be expressed as,

$$\frac{\dot{Q}_{inc}}{A_{net} \cdot G_b} = \eta_{opt,0} \cdot \mathrm{K}\ (\theta_z, \gamma_s) \cdot f_{end}(\theta_i)$$

(Heimsath A, 2013)

Where $\eta_{opt,0}$ is the optical efficiency, $\mathrm{K}\ (\theta_z, \gamma_s)$ is the incidence angle modifier, $f_{end}(\theta_i)$ is the end loss factor, A_{net} is net collector aperture area and G_b is beam radiation.

As described in (Heimsath A, 2013), certain results have been obtained for an experiment done for LFC field with North-South orientation:

"Material properties and geometrical optical errors (blocking and shading at the primary mirror field or acceptance of the secondary reflector) are varied to show a possible range for optical collector efficiency. On the upper boundary values representative for high temperature selective absorber with absorption 95.5%, transmittance 95.5% and highly reflective solar glass mirrors with reflectance 95% are assumed. The lower boundary values are represented by a medium temperature absorber with 92%, glass without anti-reflective coating, 92%, and low reflective mirrors, 85%" (Heimsath A, 2013).

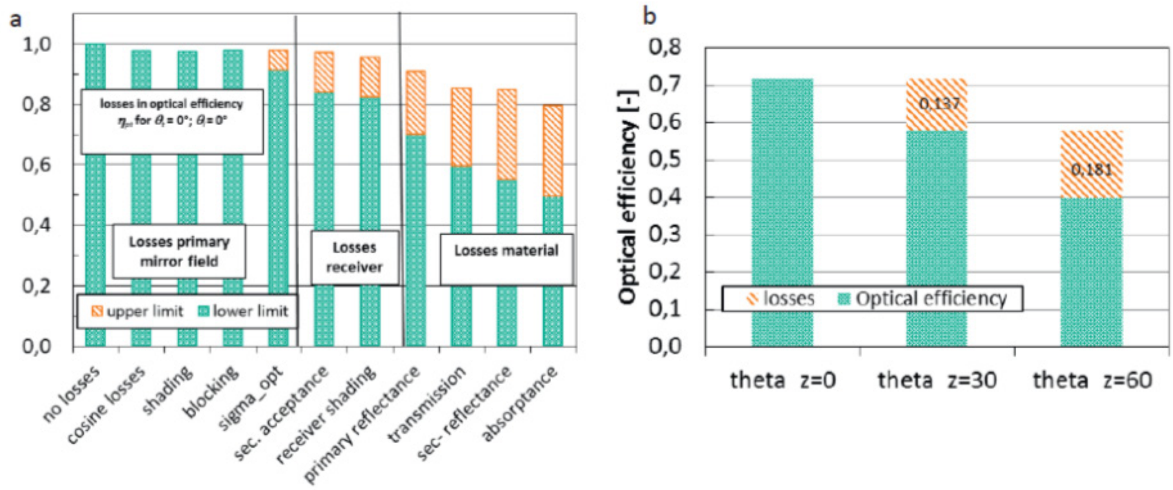


Figure 9: *(a) LFC optical losses due to primary mirror field geometry (cosine, shading, blocking, optical errors), receiver shading and acceptance of secondary geometry, and material properties (transmission, reflectance and absorptance); (b) Example for reduction of optical efficiency by angle dependent losses (mainly blocking as well as shading and optical errors) for a solar position with large influence, for* γ_S *=30° and θz =0°/30°/60°.*
(Heimsath A, 2013)

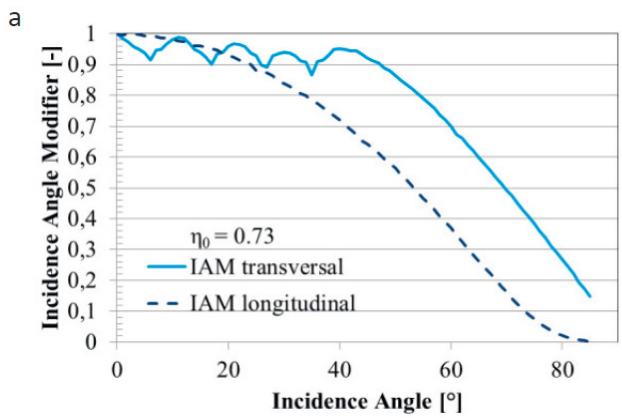


Figure 10: *Incidence angle modifier in transversal and longitudinal direction in* 1^0 *steps.*
(Heimsath A, 2013)

"For real collector installations the length of the collector rows is limited due to site requirements. The influence of end loss is increasing with shorter collector lengths and larger zenith angles". (Heimsath A, 2013)

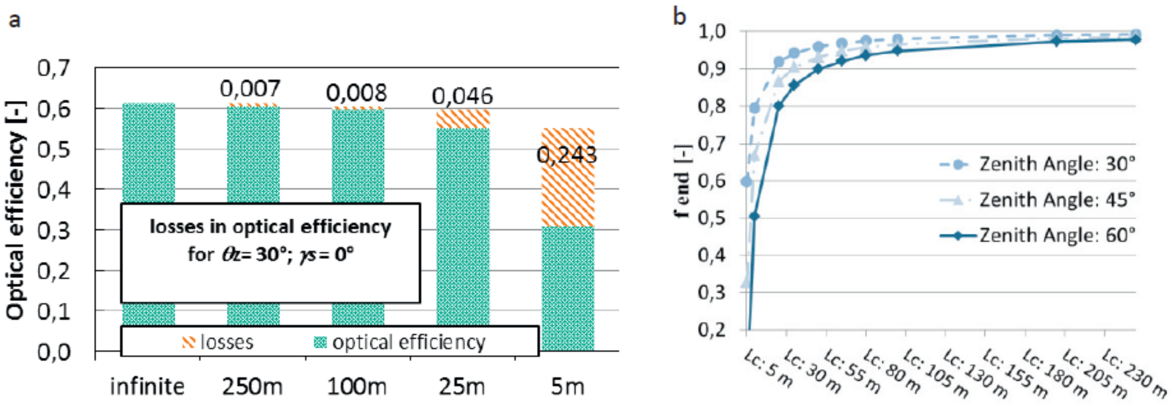


Figure 11: *(a) Order of magnitude of end loss (orange) for different collector lengths lc in m; (b) Increase of end loss factor in dependence of lc for $\gamma s=30°$, $\theta z=30°/45°/60°$.*
(Heimsath A, 2013)

As presented in the result of *Figure 9*, *Figure 10* and *Figure 11*, the overall efficiency can be estimated between 45% to 50% by assuming the other parameters like maintenance practices (e.g.; cleaning of solar panels) are maintained at optimum level.

With the North-South orientation, a higher annual surface effectiveness of around 95% can be obtained for a country like Sri Lanka (Latitude between $5^0 – 10^0$) as shown in *Figure 12*.

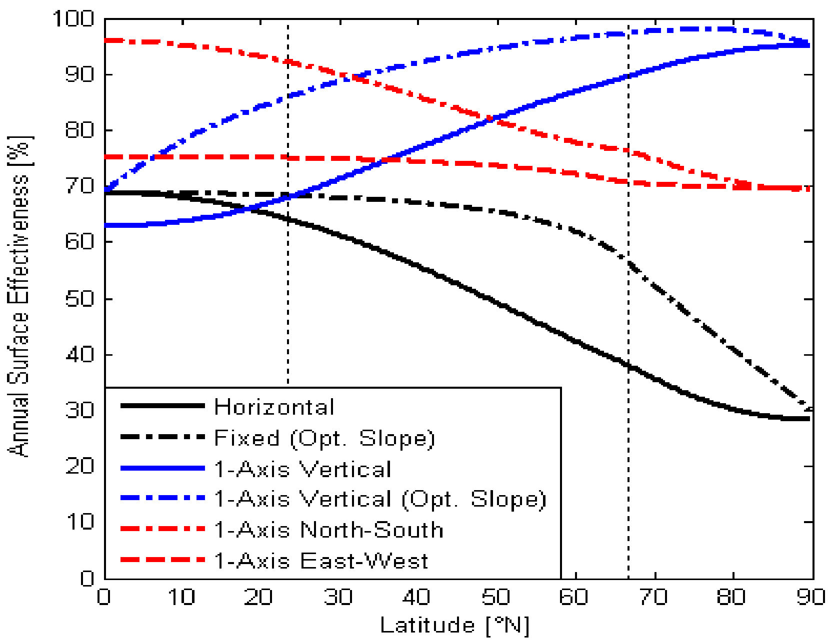


Figure 12: *Annual surface effectiveness for different tracking systems*
(Spelling, 2011)

2.1.2.2.4 Field Optimization

When designing a LFC system, there are some certain primary parameters to be considered like the width and the length of the complete collector, width of individual mirror strips, gap between mirrors and height of the absorber above the mirror plane. The following table describes the behavior and the optimization of these parameters. However, this project scope does not include the optimization designs of the solar field.

Table 3: *Characteristics of Fresnel solar field*

Component	**Characteristics/Optimization**
Width of the collector field	When considering a narrow field, the aperture area per one absorber is less. Then less energy is absorbed by the absorber. Much broader fields make more magnified losses due to the tracking inaccuracy and geometrical errors as the corner mirrors are some distance away from the absorber.
Length of the collector field	Longer fields need heavy support structure and heavy tracking drive mechanism. Shorter fields provide less energy per absorber area.
Width of mirror strips	Large number of mirror lines required when the mirror strips are too narrow. Broader mirror strips require broader absorber area and the astigmatism is stronger and the overall effectiveness is reduced.
Gap between mirror strips	Large gaps increase the field area and cannot utilize the available space. Small gaps increase the shading and blocking effects reducing the efficiency.
Distance to the absorber from the mirror plane	When the absorber is too close to the mirror plane the effects due to shading, blocking and low incidence angle will be large. When the absorber is too higher over the mirror plane, the concentration effectiveness will be lower due to the errors in tracking system and the errors in mirror geometry.

2.1.3 Solar Energy Potential in Sri Lanka

Solar energy is by far the dominant primary source of energy that represents more than 99% of the renewable energy on planet Earth. Sri Lanka is an island located closer to the equator, lies within latitudes 5^0 55'N - 9^0 55'N and longitudes 79^0 42'E - 81^0 52'E. The country receives abundant resource of solar energy and it does not show a notable seasonal variation throughout the year. The main variation throughout the regions of the country is due to cloud cover and humidity. In the mountainous areas the radiation intensity is low whereas the dry zone having high solar intensity can be preferred for harnessing with appropriate technology.

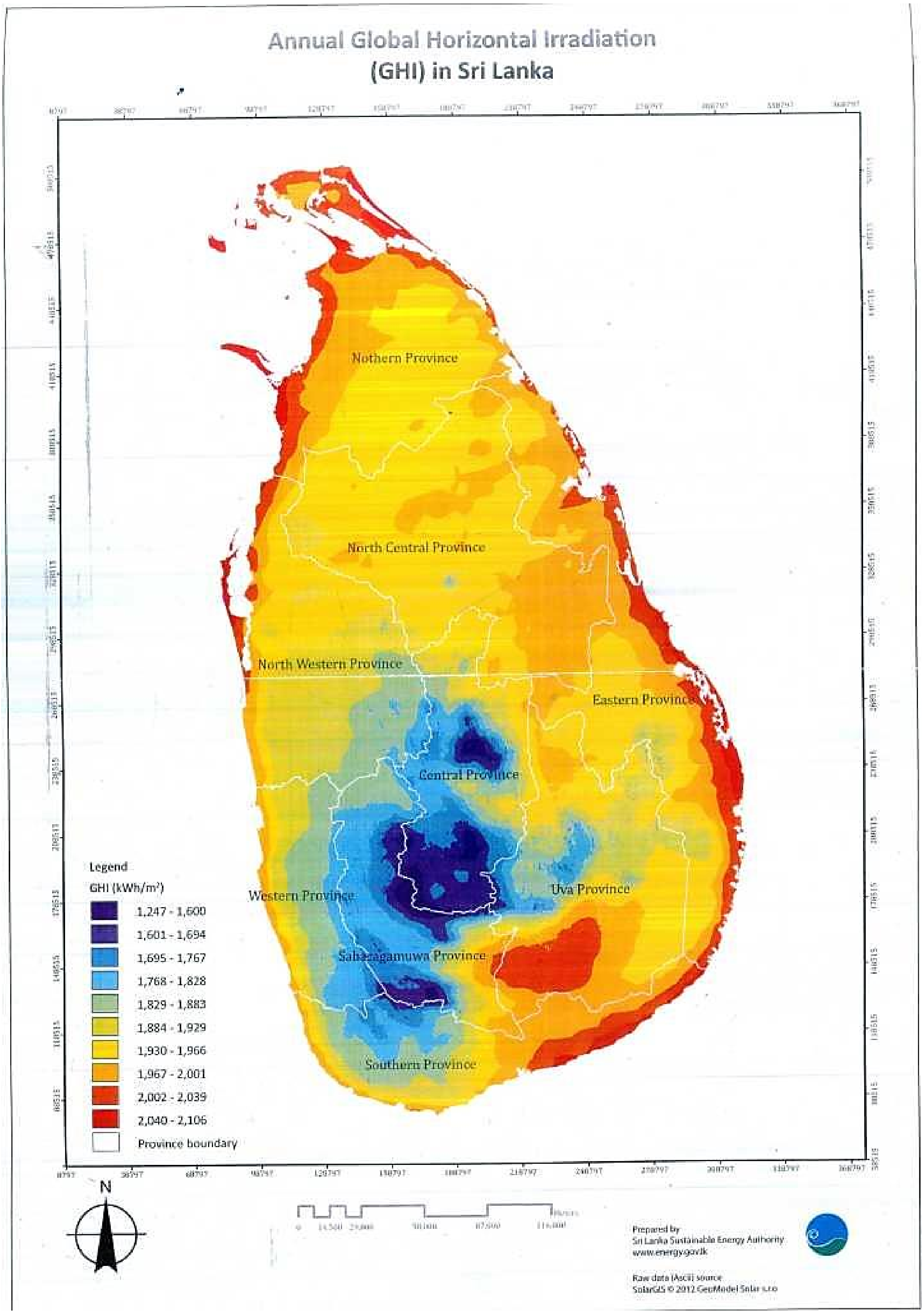


Figure 13: Annual Global Horizontal Irradiation (GHI) in Sri Lanka

(Sri Lanka Sustainable Energy Authority, 2014)

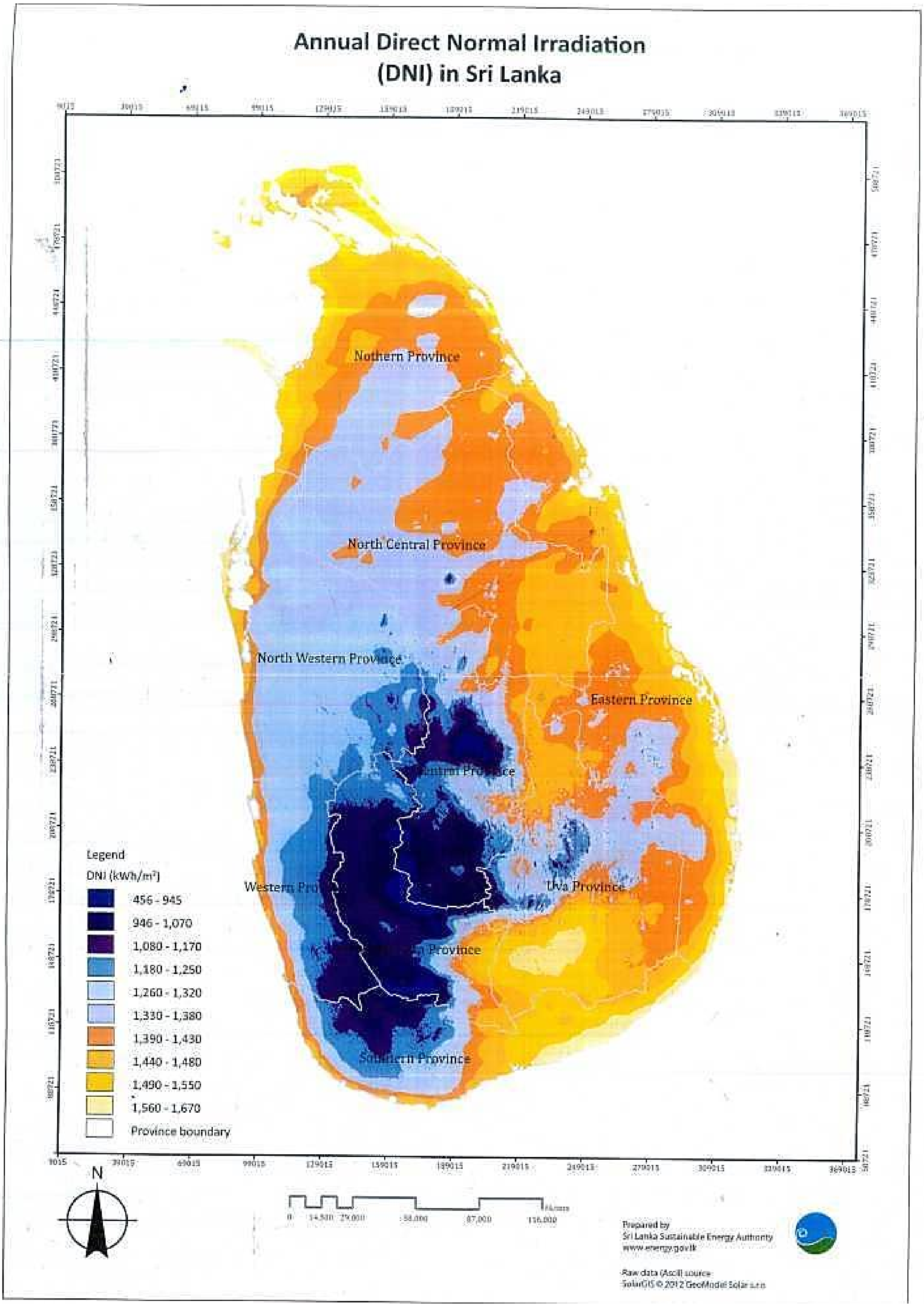


Figure 14: *Annual Direct Normal Irradiation (DNI) in Sri Lanka*

(Sri Lanka Sustainable Energy Authority, 2014)

As described in section “2.1.2.1” only the direct or the beam radiation is possible to focus to get concentrated energy and then the potential of DNI should be considered for any solar thermal applications. The Figures 13 and 14 above [*Figure 14*] show the annual GHI and DNI distribution in Sri Lanka, respectively.

According to the data available in the basic solar resource measuring stations established by SEA, the seasonal variations of the solar energy, which is an important factor for the design considerations, is given in the following table.

Table 4: *Seasonal variations of GHI in the measuring stations located in coastal area*
(Sri Lanka Sustainable Energy Authority, 2014)

Month	Daily Sum of global horizontal irradiation (GHI) / (kWh/m^2)				
	Sampoor, Trincomalee. 8.48^0N 81.29^0E	Nadukuda, Mannar Island. 9.05^0N 79.78^0E	Silawatura, Mannar. 8.74^0N 79.94^0E	Mallipurama, Puttalam. 8.07^0N 79.81^0E	Kalametiya, Southern Province. 6.08^0N 80.93^0E
January	4.71	5.02	4.66	4.66	5.06
February	5.66	6.07	5.77	5.80	5.92
March	6.52	6.67	6.52	6.55	6.36
April	6.23	6.24	6.17	6.09	5.83
May	5.90	6.12	6.08	5.64	5.50
June	5.81	5.96	5.91	5.59	5.32
July	5.79	5.85	5.87	5.67	5.38
August	5.81	5.95	5.98	5.87	5.53
September	5.98	6.13	6.22	6.08	5.67
October	5.46	5.34	5.39	5.44	5.53
November	4.49	4.39	4.30	4.53	4.79
December	4.49	4.40	4.18	4.25	4.77
Average	**5.57**	**5.68**	**5.59**	**5.51**	**5.47**

2.2 BIOENERGY

2.2.1 Biomass Technology

Bioenergy can be considered as another useful form of solar energy which is utilized indirectly in growing plants by a process called “photosynthesis”. This mechanism of plant growth takes carbon dioxide (CO_2), moisture (H_2O) from their surroundings and energy from the sunlight to convert and store as a form of useful energy or as a fuel. The substances carry this energy in the form of “biomass” and it exists in a thin layer of Earth. This is an enormous resource in terms of human energy need.

Biomass is a mixture of organic molecules that contains mainly carbon, hydrogen and oxygen. It also contains small quantities of nitrogen and heavy metals. Biomass can be taken as a fuel that interacts with the oxygen and releases energy, converting into different chemical compounds.

$$\mathbf{C_XH_Y} + (x + y/4)\,\mathbf{O_2} \;\text{------->}\; x\,\mathbf{CO_2} + (y/2)\,\mathbf{H_2O} + \textbf{Energy}$$

Biomass takes carbon dioxide from the atmosphere in the process of photosynthesis when it is at the growing stage. So that it can compensate the release of CO_2 while it burns. This can result to that there is no net change to the atmospheric CO_2 level when considering the entire lifespan of the biomass from growing stage to burning stage. Also it brings clear solution by reducing other greenhouse gases like SO_2, NO_2, etc. Compared with coal, biomass contains less ash and sulphur fractions. Hence, biomass can be undoubtedly taken as a renewable energy that can represent about 2/3 of the total potential of renewable organic fuels in the world.

Biomass can be categorized into five basic types depending on their source of supply, as listed in Table 5.

Table 5: *Types of Biomass according to the source of supply*

Type	**Description/Source**	**Example**
Virgin wood	Natural yield from forestry, residues from the wood processing	Firewood, wood charcoal, saw dust
Agricultural residues	Residues from the agricultural field after the harvesting, residues produce in the food processing	Hay, Paddy husk,
Food waste	Post-consumer waste, excesses from the food manufacturing process	Coconut shell
Industrial waste	Excesses or co-products by the industrial manufacturing processes	Municipal solid waste (MSW)
Energy crops	Forced grown selective crops for the energy applications	Gliricidia sepium, Calliandra calothyrsus

However, as a downside, biomass has relatively low energy density. Consequently higher volume is needed to produce one unit of energy. This is one major constraint as it involves higher transportation costs and larger storage volume demand. Biomass contains considerable amount of moisture depending upon the type of biomass, weather conditions and the time of drawing out (since harvesting). Removing moisture is an energy consuming process that can be covered from the stored energy in the fuel itself or by an external source of energy. This issue reduces the useful energy that can be extracted from the fuel and ultimately reduces the efficiency.

Table 6: *Characteristics of biomass fuels found in Sri Lanka*
(Sri Lanka Energy Managers Association, 2000)

Fuel	**Moisture content (%)**	**Ash content (%)**	**Size**	**Heat Value (MJ/kg)**
Wood chips	30 – 50	1	10% < 5 mm 1 % > 100 mm	9.0
Forest residue	45 – 55	2 – 5	1-2% > 150mm 20-30%< 5mm	8.4
Bark Sawdust	45 – 60	1 – 3	Bark 0 – 100mm	7.3
Pellets, Wood	10 – 15	1 – 2	Depending on machine	15.9
Briquettes of wood waste	8 – 12	1	Depending on machine	17.0
Peat Shredded	50	1 – 10	< 10x15 mm	9.8
Peat pieces	35 – 50	1 – 10	50 x 100 mm	7.5
Bagasse	50	1 – 3		7.5
Charcoal	-	3 – 4	-	24.2
Straw	15	4	Bails	14.4

Depending on the physical properties of the biomass and due to issues like low energy density and high moisture content, there are some pre-processes involved with the biomass to make it a more convenient fuel. Suitable methods are selected as a required pre-process depending on their available properties and on the requirements and purpose of fuel application. These processes are described below.

The biomass at the harvesting point represents a variety of ranges of lengths and sizes. There are several physical processes to make it more convenient or a more improved version for the application.

- Cutting to uniform length – This may be around 25-50 cm for domestic cooking purposes and may be around 2-3 m as to make easy for handling, transport and storage for the other commercial applications.

- Chipping – This process greatly improves the density of the biomass making the handling, transporting and storing easier. This is very popular biomass improving pre-process especially for the commercial energy applications.

- Grinding or shredding – In this process the equipment like Shredders, hammer mills, and tub grinders are used to reduce the biomass volume.

Raw biomass has high moisture content and depending on the properties of the application and the conversion equipment it might be applicable to use this raw biomass at wide range of moisture levels. But typically the moisture level 25-30% is maintained to make it as a more efficient fuel. Two major drying processes called “Active” and “Passive” methods are used to lower the moisture level after harvesting.

- Passive drying – Relatively slow process which requires less energy. Required moisture level up to 25-30 % can be achieved but for any further improvements it is required to go for the active drying process.
- Active drying – Relatively fast process which requires energy. High quality fuels can be achieved but it would not be feasible sometimes as it associates with relatively high costs.

By means of the physical densification and moisture removing processes as described above, the energy density is improved and the raw biomass is converted to more convenient as a biofuel.

2.2.1.1 Biomass Conversion Technology

Type of biomass, characteristics of the application and the physical properties like energy density and moisture content are the most important parameters to consider when selecting the most appropriate conversion technology. This can be a thermochemical or biochemical process. Chemical properties, volatility, heat content and the chemical reaction characteristics are the other areas to consider.

Thermochemical conversion comes mainly in three types called “Direct combustion”, “Gasification” and “Pyrolysis” while the biochemical conversions can be “Anaerobic digestion” or “Fermentation”. Only the thermochemical conversion is the focus of this project.

- Direct Combustion – Relatively dry biomass like wood and straw can directly be combusted to obtain energy for suitable applications. This has been very popular in domestic cooking and space heating. This is very well applicable method in Sri Lanka for the heating, drying and steam requirements in the small scale industries like tea factory, rubber factory and hotels. This is a simple method and would be feasible for the commercial applications if the efficiency of the overall system is well maintained through the proper technologies. This project explores this method in the view of technology advancement, fuel supply chain and feasibility analysis.

- Gasification – Biomass is heated with the limited oxygen supply to produce a gaseous fuel (mixture of combustible components) which is more convenient for other applications like gas engines connected to power generators.

2.2.1.2 Biomass boiler

Different types of biomass boilers that convert bio-energy into heat energy by means of combustion are available. These types are depending basically on the source of the biomass. As described above there are various types of biomass and their upgraded versions like liquid and gaseous biofuels can be utilized in various types of boiler equipment.

The present project focuses on firewood boilers, which can be further divided as log boilers, wood chip boilers and pellet boilers. In the log boiler, the fuel wood is normally loaded manually and they are suitable for smaller applications like domestic water heating. Commercial systems are available with some little modification to the type of fuel and to the fuel feeding system. When the required labour is available, these type of boilers can be feasible due to low cost and simple technology. Wood chip boilers are more comfortable than the log boilers but they are relatively high in capital cost and the space requirement is also high compared to wood pellet systems. Pellet boilers are high density, more compact systems, which can be fully automated. They have a control system with comparatively low capital cost but the fuel cost is high since it needs to undergo more advanced drying and densification process. The space requirements for pellet storage and pellet burner are less compared to wood chip systems.

2.2.2 Bioenergy and biomass potential in Sri Lanka

Biomass can be obtained from different sources like residues left as plant materials during the post harvesting period, organic wastes such as Municipal Solid Waste (MSW) and sewage sludge and the residues left in the forest. These materials such as Rice husks and firewood can simply be burnt to produce energy and this has been a common traditional source of energy for most of the developing countries. But in the recent decades new biomass such as purposely cultivated energy efficient crops are becoming popular in large commercial stage that produces electricity, heat or any other form of upgraded fuel like liquid or gaseous biofuels.

Biomass is still the largest source of primary energy supply in Sri Lanka. According to the annual report 2013, the share of biomass is at 43.3% of the total primary energy supply in the country. But the exact figures cannot be accurately accounted as it is being the most common energy supply in the domestic sector for cooking purposes. Biomass has come to the electrical power generation sector as well. It is categorized into "New Renewable Energy" (NRE), which shows rapid growth for the last decade and this has been a success story through the government-supported renewable energy policy implementations such as the feed-in-tariff.

There is a huge potential for biomass energy plantation in Sri Lanka having approximately 0.72 million hectare of estimated land which accounts more than 10% of the total land in the country. Biomass comes in different forms. The most common forms of biomass available in Sri Lanka are Fuel Wood, Municipal Waste, Industrial Waste and Agricultural Waste (Sustainable Energy Authority).

Table 7: *Primary Energy Supply by source in Sri Lanka*
(Sri Lanka Sustainable Energy Authority, 2013)

Source	Energy/PJ
Traditional Biomass	201.6
Petroleum	171.8
Coal	20.1
Major Hydro	60.4
New Renewable Energy	12.0
Total	**465.9**

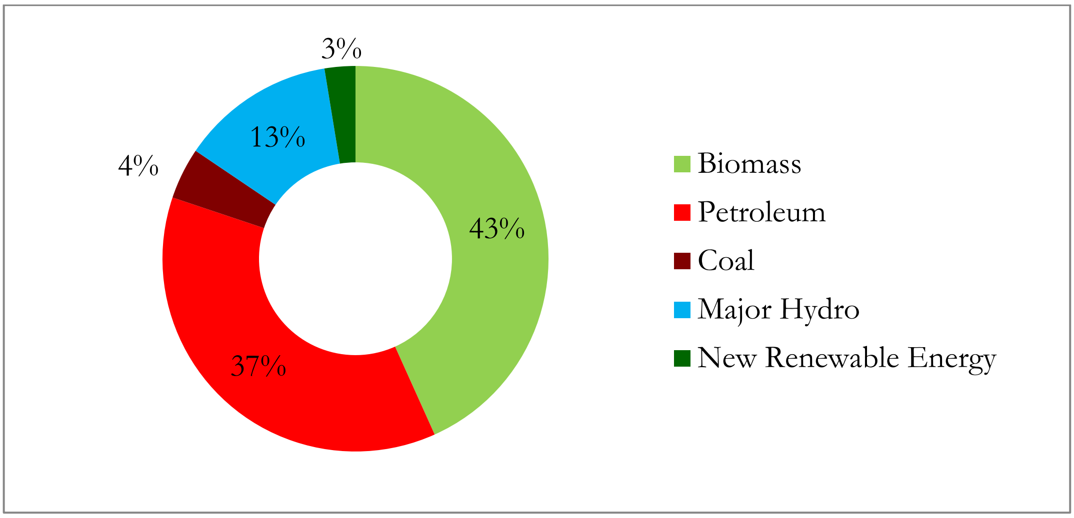


Figure 15: *Share of Primary Energy Supply by source in Sri Lanka*
(Sri Lanka Sustainable Energy Authority, 2013)

Gliricidia sepium is very popular fuel wood as they are fast growing and it can yield 20-25 tons of fuel from a hectare. There are many ways that these plantations can be established without a significant interference to the food crops achieved as a multi-crop in home gardens, as an intercrop in coconut plantations, as shade for tea plantations or as a multi crop for reforestation (Jayasinghe, 2014).

Dendro power which is known as generating electricity from sustainably grown biomass is a well suitable power source for the tropical countries like Sri Lanka as it has potential to generate electricity throughout the year. Villages in Sri Lanka have enough bare lands to launch fuel wood plantations which can be used as a replacement of the fossil fuel. So that this is a vital source for meeting the non-conventional renewable energy targets while it delivers vital environmental and socioeconomic benefits.

3 SYSTEM PROPOSAL

3.1 Overview of the hotel unit

Process heat requirement in a 5-star hotel equipped with in-house laundry, having room capacity for accommodating a maximum of 200 guests, is selected as an application ground for implementing the hybrid technology. The site location is selected as the "East Coastal" area by considering features like high tourist attraction, high solar potential and solid biomass supply.

Considering the abovementioned studies on tourist industry and the availability potentials for solar and bioenergy resources in the locality, the following basic selections can be obtained and summarized as the main features of the particular hotel unit for the design considerations.

Table 8: *Basic features of selected hotel unit for design considerations*

Feature	**Value/ Description**	**Cross-reference**
Guests capacity of the hotel	200 (max)	
Estimated average annual occupancy ratio	65%	
Maximum daily occupancy	100 %	
Minimum daily occupancy	45 %	
Location of the hotel situated	South-East coastal	*Figure 16: **Site location***
Average Ambient Temperature	28 ^{0}C	*Table 9*
Annual Rainfall	1000 – 1500 mm	*Table 9*
Annual solar irradiance	1620 kWh/m^2	Section 2.1.3, Solar Energy Potential in Sri Lanka (*Figure 14: Annual Direct Normal Irradiation (DNI) in Sri Lanka*)
Average daily Solar irradiance	4.44 kWh/m^2 (15.98 MJ/m^2)	
Maximum daily Solar irradiance	5.33 kWh/m^2	As per *Table 4*, the variation in maximum GHI for the locations "Kalametiya" and "Sampoor" show 16% and 17% variation from the average value. It is assumed that the intensity of variation in DNI is same as to GHI. Then the maximum daily DNI for the site location is assumed as 20% above average DNI.

3.2 Site survey and selections for CSP application

Site location is considered as the south-east coastal area of the country, as shown in *Figure 16*.

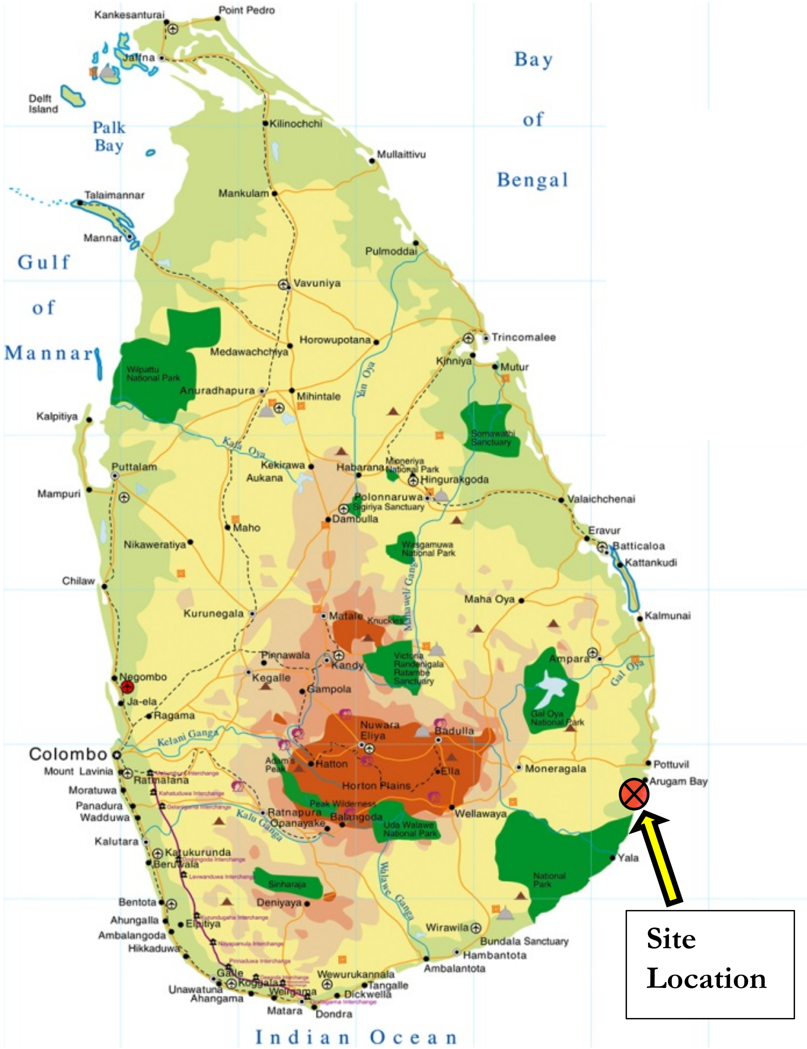


Figure 16: Site location

Data specific to the site location can be given as below, see Table 9.

Table 9: Data related to the solar installation

Data/Parameter	Value	Reference
Annual Direct Normal Irradiation (DNI)	1620 kWh/m^2	Section 2.1.3 (*Figure 14: Annual Direct Normal Irradiation (DNI) in Sri Lanka*
Average Ambient Temperature	28 ^0C	(Department of Meteorology)
Annual Rainfall	1000 – 1500 mm	(Department of Meteorology)

3.3 Site survey and selections for biomass application

Other than the different types of biomass and various pre-process methods for the different applications, it is required to assess the entire supply chain considering the field of origin, supply centers, transportation methods and to the pre-processing and storage options. These all options together with the energy conversion methods will determine the most appropriate type of biomass to be used.

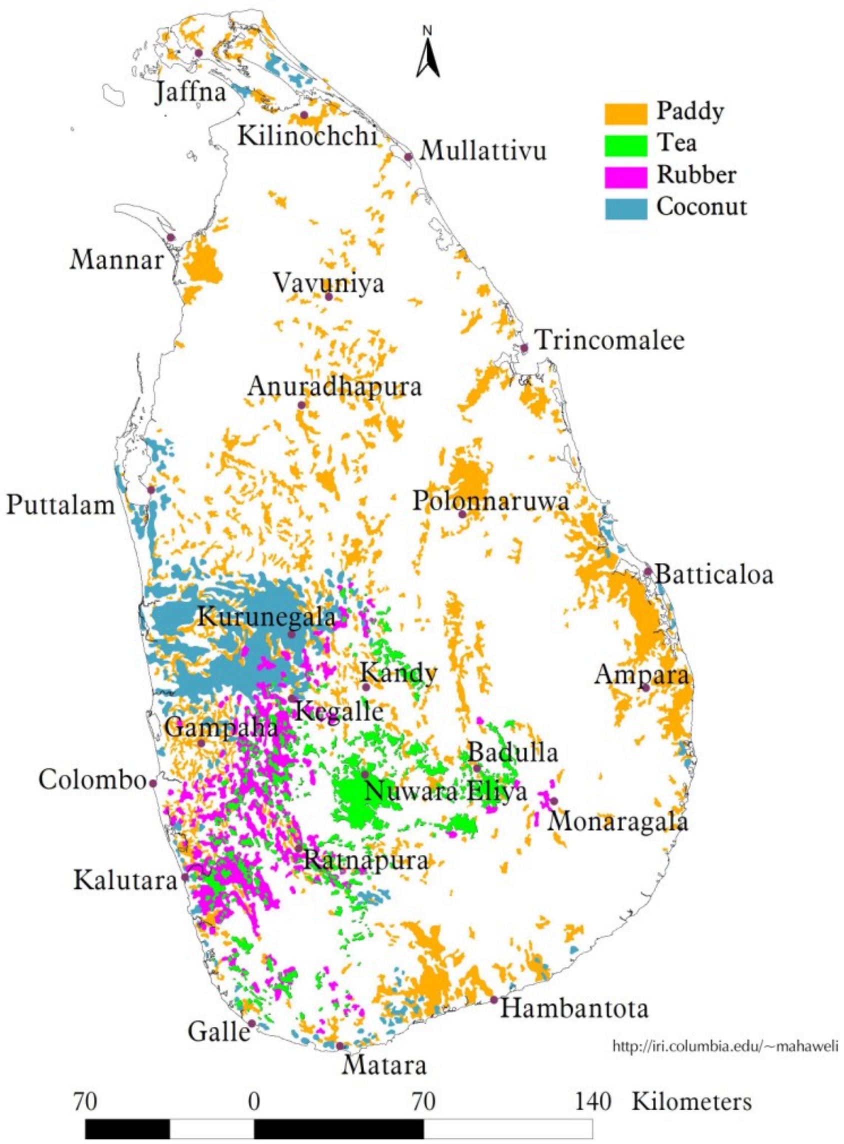


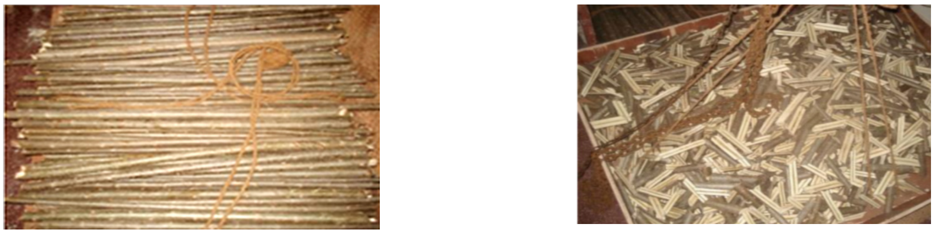
Figure 17: Land distribution on main plantations

(Ariyawansa, 2014)

As described in the sections above, the following features can be selected for the biomass system as given in *Table 10*.

Table 10: *Selections for the biomass application*

Feature	Selection/value	Criteria/ Description
Type of biomass (fuel)	*Gliricidia*	Huge potential to grow in the eastern side in Sri Lanka (land availability, suitable weather, labour availability), and solid supply can be assured. As given in *Figure 17*, huge land extent is engaged in paddy cultivation in "Ampara" area near to site location. So the climate is suitable for this energy crop plantation. It can be used as dedicated to this industry (mono crop) or as an intercrop plantation.
Pre-process	Cutting into pieces and natural drying	(*Figure 18* and *Figure 19*)
Energy content (HHV)	17.64 MJ/kg (4900 kcal/kg)	(UNDP, 2013)
Moisture content of fuel at burning stage	20%	Needs 20 days of natural drying (*Figures 18* and *19*)
LHV	13.7 MJ/kg	(Jayasinghe, 2014)



a) Gliricidia Sticks with Bark   b) Split Gliricidia Pieces

Figure 18: *Gliricidia as a fuel*
(Jayasinghe, 2014)

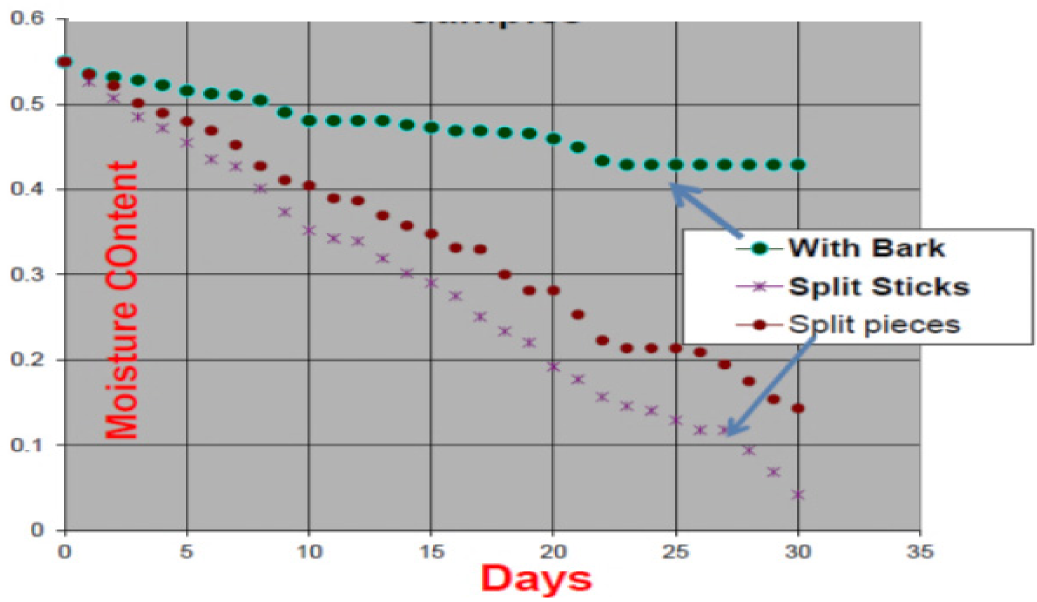


Figure 19: *Natural Moisture reduction of different samples of Gliricidia*
(Jayasinghe, 2014)

3.4 Requirements and conditions of proposed hotel unit

3.4.1 Hot water requirement

Features of the hot water requirement and the relevant standard code/source are given below in Table 11.

Table 11: *Design guidelines to the hot water system*

Parameter	**Value**	**Source**
Daily consumption per room (in Hotels/motels)	57 l/day	(US Army Corps of Engineers, 2011)
Consumption per meal (restaurants)	9 l/per meal	(US Army Corps of Engineers, 2011)
Minimum and Maximum Storage temperature	45°C and 65°C	CIBSE Guide G (Public Health Engineering, **Section 2.4.7.2**) – March,2004

According to the above conditions given in *Table 11*; and with the practical parameters and common practice (for tropical climate) found during the site visits, the following statements and the certain assumptions as given in *Table 12*; can be made for the design proceedings.

Table 12: *Hot water system design data*

Parameter	**Value**
Hot water consumption for bath and shower per guest	25 l/guest
Daily hot water consumption for kitchen/restaurant, and other common uses (per guest)	20 l/guest
Storage temperature	60.0 °C

For the hotel with a capacity of 200 guests

Maximum total daily hot water (@ 60°C) demand = (25 + 20) l/guest × 200 guests

= 9,000 l/day

Assuming, density of water equal to 1 kg/l

Total maximum daily hot water requirement (@ 60°C) M_{HW} = 9,000 kg/day

3.4.2 Steam requirement

Required data for the steam consumption for laundry purposes was obtained from the practical recorded data and available design data. Following details similar to this project criterion are given in *Table 13*.

***Table 13**: Characteristics of steam requirement data (data survey)*

Hotel #	Guests Capacity	Maximum Laundry steam consumption rate/ (kg/h)	Service steam pressure /bar	Maximum Daily steam consumption/ (kg/day)	Condensate mass recovery	Laundry operating hours (max)
10	270	595	8.0	5,200	56 %	10 hrs
11	320	685	8.0	6,200	55 %	12 hrs

According to the above conditions given in the *Table 13* and with the practical situation found during the site visits, the following statements can be made to a hotel with 200 guests for the design proceedings.

***Table 14:** Steam system design data*

Guests Capacity	Maximum Laundry steam consumption rate/ (kg/h)	Service steam pressure /bar	Maximum Daily steam consumption/ (kg/day)	Condensate mass recovery	Laundry operating hours (max)
200	520	8.0	4,000	57 %	10 hrs

3.5 Model Design of proposed system

Section 3.5.1 and Figure 20 below present the overall schematic diagram of the proposed system model layout. The thermal energy requirement is shared among the solar panels and the biomass-fired boiler, each of them feeding into the common steam header at 8 bar pressure, from which the laundry facilities are supplied. The solar panels also deliver heat to the hot water tank for supplying the kitchen needs and room showers, while the biomass boiler could also feed thermal energy to the hot water tank through a steam flash system.

3.5.1 Schematic diagram

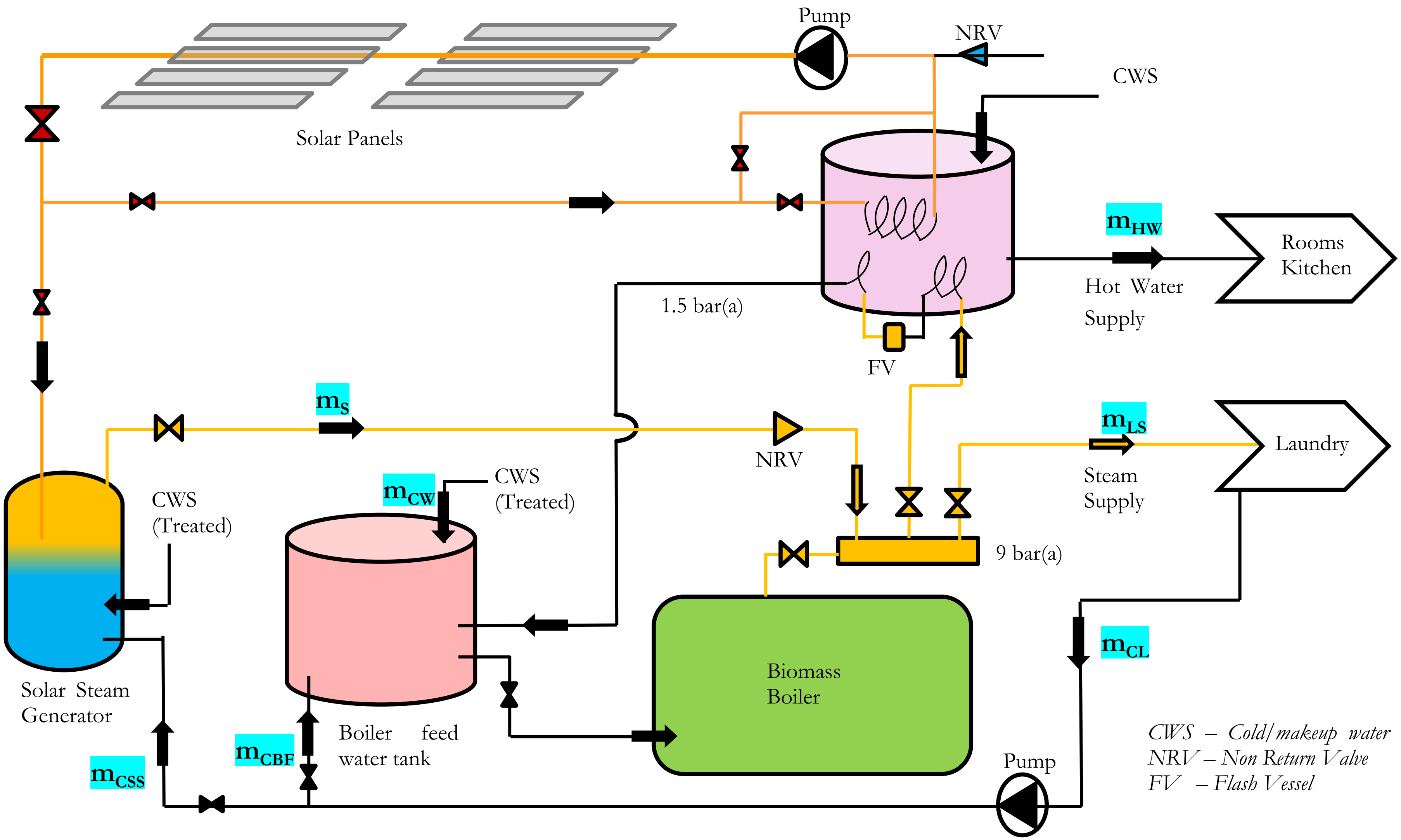


Figure 20: Schematic diagram of the system model

3.5.2 Operating technique and design considerations

a) Solar energy is harvested by Linear Fresnel type of concentrated solar modules installed on the roof of the building. The heat is transferred by pressurized water through insulated pipes. In the steam generator it produces steam to the required pressure through a direct heating method. But heat is also supplied to the hot water tank indirectly to avoid mixing with hot water supply and steam supply to prevent entering the treated water to the hot water supply.

b) It is assumed that the maximum available solar irradiance is harvested throughout the day by means of proper tracking system attached to the solar modules. North-South axis orientation is proposed as it has relatively higher surface effectiveness throughout the year as described in section 2.1.2.2.2. The tracking system theories and designs are beyond the scope of this project.

c) Hot water tank and the boiler feed water tank are controlled by Fixed Temperature Control (FTC) method. For example, when considering the hot water tank; if the temperature goes beyond the set value (65^{o}C) due to the heat supply the cold (makeup) water is supplied to the system and mixed to keep the water temperature at proper operating level (60^{o}C). When the water level of the tank reaches its maximum, all the cold water and heat supplies are shut down. Inversely, when hot water is drawn out due to high consumption, the water level in the tank is decreasing. Then the discharge valve closes when it reaches to the predefined minimum level.

d) Solar steam generator has been introduced to this system in order to collect the extra energy when the solar radiation is more than the design (daily average) value due to the seasonal effects. On the other hand, there are some situations when the total daily demand for the hot water is at reduced level than the design values due to the low occupancy level of the guests in the hotel. In these situations, the boiler is operated at low capacity since the solar steam generator provides enough steam to the system. Thus the total system design is proposed in such a way that the maximum possible solar radiation throughout the year is harvested.

e) Biomass-fired boiler is basically performing as the back-up steam supplier, but is dimensioned to cover the entire heat demand on its own. It receives feed water heated by the condensate recovery after the applications. During a low-solar day or in zero-solar situations the biomass boiler has to run at its full capacity and serves steam to all applications and to the hot water tank to sustain an uninterrupted hot water supply and to make the system fully self-reliable.

4 CALCULATION AND ANALYSIS

4.1 DETAILED CALCULATION

The daily energy demand of the hotel is dependent on the occupancy ratio of the particular day considered. Daily occupancy is a variable depending on the tourist's season variations throughout the year. Daily solar irradiance is also a variable and then the energy supply contribution from solar and biomass is varied day by day. A computer simulation tool named "BioSolar HeatApp" using the MicroSoft Excel platform has been developed for this analysis. For a given occupancy ratio and given daily solar irradiance the total energy variations and the relevant specific results are calculated by the BioSolar HeatApp program. Likewise, these repeated calculations can be done easily and anticipated results are obtained by entering the relevant data into the program. The BioSolar HeatApp program details are presented in Appendix-1.

Critical and important calculation data relevant to this design and to the system analysis are given below as the basic model calculations.

4.1.1 Maximum daily energy requirement

For the initial design purpose, the maximum demand day (100% occupancy) of the hotel is considered.

a).Daily energy requirement for hot water supply

Referring to the hot water requirement described in section 3.4.1

Daily maximum hot water heating requirement = $m_{HW}\ C_P\ (T_{HW}\text{-}T_{CS})$
(Assume, density of water equal to 1 kg/l)

= 9,000 × 4.2 × (60 – 28) kJ/day

= 1,210 MJ/day

Assume line losses and the storage tank surface losses are maintained at 8% by means of proper insulation. (These losses should be maintained within 10% (US Army Corps of Engineers, 2011)*)*

Energy requirement for hot water supply (ME_{HW}) = 1,210 × 1.08

= 1,306 MJ/day

b).Daily energy requirement for steam supply (laundry)

Amount of steam requirement (m_{LS}) = 4,000 kg/day

Steam supply pressure = 8 barg (9 bara)

Specific enthalpy of dry sat. steam @ supply pressure = 2,774 kJ/kg

Energy content rate of steam supply = 4,000 × 2,774 kJ/day

= 11,096 MJ/day

Assume 3 % line losses

Energy input to the steam supply = 11,096 × 1.03 MJ/day

= 11,429 MJ/day

Condensate mass return after laundry process = 57 % (*Table 14: Steam system design data*)

Specific enthalpy of condensate @ ambient pressure = 419 kJ/kg

Energy content rate of condensate return = 4,000 × 0.57 × 419 kJ/day
= 955 MJ/day

Assume 3 % line losses

Actual energy recovery from condensate (ME_{CL}) = 955 × 0.97
= 927 MJ/day

Assume the total energy in the condensate return is recovered by feed water heating and by feeding back into the steam generator in the solar system. (Temperature of the feed water tank for different situations is given in the case analysis in section 4.1.3)

Actual energy requirement for steam supply (ME_{LS}) = 11,429 – 927
= 10,502 MJ/day

c).Total maximum daily energy requirement

Total maximum daily energy requirement (ME_S) = ME_{HW} + ME_{LS}
= 1,306 + 10,502
= 11,809 MJ/day

4.1.2 Designing the solar system

During this maximum demand day, it is assumed that the total energy requirement for hot water supply is fulfilled by solar energy assuming that the average daily solar irradiance is received on this day. Additionally to the model calculations, it is assumed that 10% of the energy requirement for the steam supply is covered by the solar system (Solar-steam fraction F_S = 10 %). Solar-steam fraction can be increased from zero to higher values considering the rooftop space availability and the initial investment limitations.

Designed Energy supply to the system = $ME_{HW} + F_S \times ME_{LS}$
= 1,306 + 0.1 × 10,502
= 2,357 MJ/day

Assume 3 % line losses

Designed energy supply by solar to the system = 2,357 × 1.03
= 2,427 MJ/day

Annual DNI of the location = 1,620 kWh/m^2

Daily average DNI = 4.44 kWh/m^2.day = 15.98 MJ/m^2.day

Overall efficiency of the Fresnel solar system (η_{Solar}) = 45 % (Section 2.1.2.2.3)

Collector area requirement (A_M) = 2,427/(15.98×0.45)

A_M = <u>338 m²</u>

Taking the Space utilization factor as 3 (Nixon J.D., 2012)*, the total rooftop area requirement for this system installation can be calculated as;*

Total rooftop area requirement = 338 × 3 = <u>1,014 m²</u>

4.1.3 Case analysis

4.1.3.1 "Low solar" day

"Low solar" day is defined as when the solar energy is not enough to meet the energy demand of the hot water supply. In such case, the required balance of energy is delivered by the supporting steam supply generated by the biomass boiler. These types of situations normally occur during the days when the daily solar irradiance is low and the hotel is highly occupied (higher guest occupancy ratio, R_G).

<u>*Case-1;*</u>

Let's take, Occupancy ratio of the day (R_G) = 90 % (0.9)

Solar radiation (DNI_D) = 7.2 MJ/m² (2.00 kWh/m²)

<u>*a) Hot water system calculations*</u>

Amount of daily hot water requirement (@ 60°C) m_{HW} = 9,000 × 0.9

= <u>8,100 kg/day</u>

Energy requirement for hot water supply (E_{HW}) = $ME_{HW} \times R_G$

= 1,306 × 0.9

= <u>1,176 MJ/day</u>

Total energy generated by solar system = $A_M \times \eta_{Solar} \times DNI_D$

= 338 × 0.45 × 7.2

= <u>1,094 MJ/day</u>

Balance energy requirement for hot water supply
from biomass boiler = 1,176 – 1,094

= 82 MJ/day

Allow 5% line losses

Needed energy supply by boiler to hot water tank = 82.0 × 1.05

= <u>86.1 MJ/day</u>

The condensate (saturated water) is maintained at 1.5 bara after the primary and secondary heating circuits.

Specific enthalpy of condensate (saturated water @ 1.5 bara) = 468 kJ/kg

Specific enthalpy of dry saturated steam @ 9 bar	= 2,774 kJ/kg
Mass rate of needed steam supply to hot water tank	= 86100 / (2774 – 468)
	= 37.3 kg/day

After supplying energy to hot water tank, the condensate line is heading back to the boiler feed water tank for energy recovery (as shown in schematic diagram in section 3.5.1, Figure 20). The feed water tank is at ambient pressure and there will be flash steam generation inside the feed water tank from this condensate supply at 1.5 bar.

Calculating amount of flash steam generation @ ambient pressure

Amount of flash steam generation @ ambient pressure per 1kg of condensate @ 0.5 barg (1.5 bara)	= (468 – 419)/2257
	= 0.022 kg/kg
Daily amount of flash steam generation	= 0.022 × 37.3
	= 0.81 kg/day
Energy recovery by flash steam	= 0.81 × 2257
	= 1.83 MJ/day
Amount of steam requirement (m_{LS})	= 4,000 × R_G
	= 3,600 kg/day
Condensate mass on return (m_{CL})	= 3,600 × 0.57
	= 2,052 kg/day
Condensate energy recovery (after laundry)	= ME_{CL} × R_G
	= 927 × 0.9
	= 817 MJ/day
Actual energy requirement for laundry (E_{LS})	= ME_{LS} × R_G
	= 10,502 × 0.9
	= 9,452 MJ/day
Total daily energy requirement (E_S)	= E_{HW} + E_{LS}
	= 1,176 + 9,452
	= 10,628 MJ/day
Amount of Steam requirement to laundry	= 3,600 kg/day
Amount of Steam requirement to hot water heating	= 37.3 kg/day
Total steam generation	= 3,600 + 37.3
	= 3,637 kg/day'

Condensate mass recovery after hot water heating = 37.3 kg/day

Condensate mass on return after laundry = 2,052 kg/day

Total mass on return to feed water tank = 37.3 + 2,052
= 2,089 kg/day

From mass conservation;

Makeup cold water supply to feed water tank (m_{CW}) = 3,637 – 2,089
= 1,548 kg/day

Finding the boiler feed water temperature, T_F

Energy supply by cold water = E_{CW} C_P (T_{CS} - T_F)

= 1,548 × 4.2 × (28 - T_F)

Energy supply by condensate coming from hot water = 1830 + 37.3 × 4.2 × (100 - T_F)

Energy supply by condensate coming from laundry = 3,600 × 4.2 × (100 - T_F)

From energy conservation;

1,548 × 4.2 × (28 - T_F) + 1830 + 37.3 × 4.2 × (100 - T_F) + 3,600 × 4.2 × (100 - T_F) = 0

Boiler feed water temperature, T_F = 69.5 ^{0}C

4.1.3.2 "High solar" day

"High solar" day is defined as when the solar system generates more energy than the energy demand of the hot water supply. In such case, the excess energy is utilized by generating steam. These types of situations normally occur during the days when the daily solar irradiance is high.

Case-2;

Let's take, Occupancy ratio of the day (R_G) = 90 % (0.9)

Solar radiation (DNI_D) = 18.0 MJ/m^2 (5.00 kWh/m^2)

Amount of daily hot water requirement (@ 60^{o}C) m_{HW} = 9,000 × 0.9 kg/day
= 8,100 kg/day

Energy requirement for hot water supply (E_{HW}) = ME_{HW} × R_G
= 1,306 × 0.9
= 1,176 MJ/day

Total energy generated by solar system = $A_M \times \eta_{Solar} \times DNI_D$
= 338 × 0.45 × 18.0
= 2,734 MJ/day

Excess energy supply by solar system to steam generation = 2,374 – 1,176

= 1,559 MJ/day

Allow 2% line losses

Actual energy received to steam generation = 1,559 × 0.98

= 1,528 MJ/day

Condensate energy recovery (after laundry) = $ME_{CL} \times R_G$

= 927 × 0.9

= 817 MJ/day

Actual energy requirement for laundry (E_{LS}) = $ME_{LS} \times R_G$

= 10,502 × 0.9

= 9,452 MJ/day

Total daily energy requirement (E_T) = $E_{HW} + E_{LS}$

= 1,176 + 9,452

= 10,628 MJ/day

Actual energy received to steam generation by solar = 1,528 MJ/day

Energy requirement to steam generation by boiler = 9,452 – 1,528

= 7,893 MJ/day

Allow 2% line losses

Total energy supply by biomass boiler = 7,893 × 1.02

= 8,051 MJ/day

Solar/Biomass energy supply ratio to laundry steam supply

= 1,528 : 7,893

= 16% : 84%

Assume that the condensate mass return circulated in such a way that the mass ratio is equal to the energy generation ratio of each system.

Amount of steam requirement (m_{LS}) = 4,000 × R_G

= 3,600 kg/day

Condensate mass on return (m_{CL}) = 3,600 × 0.57

= 2,052 kg/day

Condensate mass return to solar steam generator (m_{CSS}) = 2,052 × 16%

= 333 kg/day

Condensate mass return to boiler feed water tank (m_{CBF})= 2,052 × 84%
= 1,719 kg/day

Specific enthalpy of dry sat. steam @ supply pressure = 2,774 kJ/kg
Specific enthalpy of cold water = 117 kJ/kg

Considering solar steam generator, Let's take,

Steam generation by solar system = m_S

Energy output as steam = m_S × 2774 kJ/day

Energy input by condensate = 333 × 419 kJ/day

Energy input by cold water = (m_S – 333) × 117 kJ/day

Energy input by solar system = 1528 × 1000 kJ/day

From energy conservation;

333 × 419 + (m_S – 333) × 117 + 1528 × 1000 = m_S × 2774

Steam generation by solar system (m_S) = 613 kg/day

Steam generation by biomass boiler = 3600 – 613
= 2,987 kg/day

Condensate mass return to boiler feed water tank = 1,719 kg/day

From mass conservation;

Cold water supply to feed water tank (m_{CW}) = 2,987 – 1,719
= 1,268 kg/day

Finding the boiler feed water temperature, T_F

Energy supply by cold water = m_{CW} C_P (T_{CS} - T_F)
= 1,268 × 4.2 × (28 - T_F)

Energy supply by condensate coming from laundry = 2,987 × 4.2 × (100 - T_F)

From energy conservation;

1,268 × 4.2 × (28 - T_F) + 2,987 × 4.2 × (100 - T_F) = 0

Boiler feed water temperature, T_F = 69.4 ^{0}C

4.1.4 Annual energy analysis

Same solar fraction (F_S) = 10% as described in section 4.1.2 is interrelated for this model calculation.

The annual average occupancy R_G = 65 %

Annual average DNI (DNI_D) = 4.44 kWh/m^2 (15.98 MJ/m^2)

The important results relevant to above data can be obtained by following the same calculation as shown in the model calculations in section 4.1.3.2. These results can easily be obtained using the "BioSolar HeatApp" program by entering the relevant R_G and DNI_D values.

Average daily energy demand for hot water Supply	= 849 MJ/day
Average daily energy demand for steam Supply	= 6,826 MJ/day
Total energy requirement	= 7,676 MJ/day
Total energy generated by solar system	= 2,428 MJ/day
Energy supply by biomass boiler	= 5,352 MJ/day

Then,

Total annual energy demand (E_T)	= 7,676 × 365
	= 2,801,587 MJ/yr.
Annual energy supply by solar system (E_S)	= 2,428 × 365
	= 886,288 MJ/yr.
Annual energy supply by biomass boiler (E_B)	= 5,352 × 365
	= 1,953,605 MJ/yr.

4.1.5 Designing the biomass boiler

To get the maximum required capacity of the boiler, it is assumed that there can be situations that the solar irradiance throughout the day is zero. During such entirely rainy days with heavy cloud cover (zero-solar day), the biomass-fired boiler has to provide all the heating requirements.

This "Zero solar" day comes under "Low Solar" situation described in section 4.1.3.1. According to the calculations give in that section, the steam requirement for hot water supply and the feed water temperature can be obtained by entering R_G=100% and DNI_D=0,

Steam requirement for hot water supply		= 595 kg/day
Feed water temperature	T_F	= 74.6 ^{0}C

Assuming the recovery period for hot water steam requirement is within 4 hours

Hourly steam requirement for hot water supply	= 595/4
	= 148.7 kg/h

Steam demand of the laundry as described in section 3.4.2

Hourly maximum steam requirement by laundry	= 520 kg/h

Total steam requirement
(Dry saturated steam @ 9 bara) = 520 + 148.7
= 668.7 kg/h

Enthalpy of steam @ 9 bara h_g = 2,774 kJ/kg
= 663 kcal/kg

Capacity rating of biomass boiler, = Actual rating × (h_g - T_F) / 540
= 668.7 × (663 – 74.6)/540
= 729 kg/h

With the available market ranges, the recommended size of the boiler (F & A rating) = 750 kg/h

Table 15: *Summary of features of boiler operation*

Parameter	**Value**	**Description**
Boiler Capacity (F & A rating)	750 kg/h	Section 4.1.5
Operating pressure	8 barg (9 bara)	Depending on the system requirement
Maximum steam demand rate	668.7 kg/h	
Maximum daily steam demand	4,595 kg/day	In a zero-solar day
Maximum heat demand from boiler	11,809 MJ/day	
Boiler operating hours	10 hours	

4.2 MODELING AND OPTIMIZING THE SYSTEM

4.2.1 Initial cost

Normally the renewable energy technologies are capital intensive. When considering the cost of CSP technology, the most critical part is the solar module. The cost of the solar modules can be categorized as follows.

- Material cost
- Fabrication cost
- Transportation cost
- Field assembly and installation costs

Currently, more than 80% of CSP power plants in operation or under construction are based on the trough technology (International Renewable Energy Agency, 2012). Therefore, the most of the available cost data is relevant to this technology as it is been the most mature technology among the CSP options. A detailed cost breakdown for a 50 MW_{el} parabolic trough power plant (similar to the Andasol plant in Spain) with the estimated investment of USD 364 million, is as follows:

"*The solar field equipment (510 000 m²) is the most capital-intensive part (38.5 %) of this parabolic trough system. The thermal energy storage system accounts for 10.5% of total costs, with the salt and the storage tanks being the largest contributors to this cost. Labour represents 17% of the project cost and is an area where local content can help reduce costs in developing countries. Conventional plant components like power block and grid connection accounts as 14% while the other indirect costs like project development, project management and financing cost shows 19.5% of the capital investment*" (International Renewable Energy Agency, 2012).

India has shown a considerable growth in CSP technology thus there are some certain cost analyses available with this technology. According to one such analysis, "*It has been estimated that an LFR solar field, based on aperture area, must cost below 281 $/m^2 to be competitive with other CSP technologies. Typical costs for an LFR system are around 235 $/m^2. The Solar Mission has proposed a 30% capital cost subsidy for solar energy technologies implemented in India, therefore, a value of 165 $/m^2 is assumed for the cost of the solar field*" (Nixon J.D., 2012).

Following the data above, the cost of the solar field in this proposed system is taken as 165 $/m^2 while the additional cost involved with the balance of system like solar steam generator, piping and equipment outside to the solar field is assumed to be 30% of the cost of the solar field.

The cost of biomass boiler is assumed to be $ 54,000 per tonne of steam produced per hour (Nixon J.D., 2012). India has shown a significant development in boiler manufacturing but Sri Lanka is a beginner to this technology. Therefore, considering the technology gap, it is assumed that the boiler and the installation cost given for a 1 tonne boiler ($ 54,000) are applicable for a boiler capacity with 750kg/h for our case. The additional piping and equipment outside to the boiler system is assumed to be 20% of the cost of boiler.

As this is a new technology to Sri Lanka, there are some uncertainties involved with the cost analysis. Therefore the indirect cost like project development, project management and including contingencies is assumed at a higher margin of 20% of the initial cost.

The estimated initial cost for the proposed solar-biomass hybrid system with solar fraction (S_F) of 10% (as described in the model calculations in section 4.1.2) is given below in *Table 16*.

***Table 16**: Estimated initial cost of solar-biomass hybrid system with solar fraction of 10%*

Description	Rate	Cost/($)
Solar field (reflectors, receivers, support structure, tracking system, and other equipment	165 $/m^2	55,702
Additional piping and equipment	30%	16,710
Biomass-fired boiler (material and installation cost)	$ 54,000/(1 tonne/h steam)	54,000
Additional piping and equipment	20%	10,800
Other (Indirect cost, Contingencies)	20% of all capital costs	27,442
Total Capital Cost (C_{ISB})		**164,655**

4.2.2 Operational cost

Operational & maintenance cost of plant and equipment for a biomass boiler can be taken as 28% of the initial cost of boiler (UNDP, 2013). Most of the available O & M cost for solar systems is related to large scale solar power plants that generate electricity. It is about 1% of the total investment (International Renewable Energy Agency, 2012) and these cost details are not comparable for a medium scale solar application that generates process heat. Maintenance cost of plant and equipment in a solar field is a relatively very low value but the most critical part for such medium scale project would be the labour or staff. For this cost estimation, it is assumed that 1 supervisor (skilled labour) and 4 technicians (semi-skilled) are engaged in O & M works of the solar system. Depending on the current market rate in Sri Lanka, the annual wages of skilled and semi-skilled labour are taken as $ 4,000 and $2,500 respectively.

Insurance cost is estimated as 1% of the total investment (International Renewable Energy Agency, 2012).

The annual biomass fuel cost is as follows:

Same solar fraction (F_S) = 10% as described in section 4.1.2 is correlated for this model calculation.

The annual average occupancy R_G = 65 %

Annual average DNI = 4.44 kWh/m^2 (15.98 MJ/m^2)

Annual energy supply by biomass boiler = 1,953,605 MJ/yr.

It is assumed that the overall efficiency throughout the year of the boiler (η_{Boiler}) = 67% (UNDP, 2013)

So that, Annual biomass feedstock consumption is given by

$$M_{BIO} = \frac{1{,}953{,}605}{\eta_{Boiler} \times LHV}$$

LHV of biomass (Gliricidia) is taken as 13.7 MJ/kg with the moisture content of 20% (Jayasinghe, 2014).

Then, M_{BIO} = 1,953,605/ (0.67 × 13.7)

= 212,834 kg/yr.

Cost of the biomass is assumed to be 0.057 $/kg referring to the present market values, where the pre-processing, transport and storage costs are included.

Annual cost of biomass fuel supply = 212,834 × 0.057

= 12,132 $/yr.

The total annual operational cost is given in Table 17.

Table 17: *Estimated annual operational cost of solar-biomass hybrid system with solar fraction of 10%*

Description	**Rate**	**Cost/($/yr.)**
O & M	28% of initial cost of solar field and biomass boiler.	29,677
Insurance	1% of the investment	1,647
Fuel (Gliricidia)	0.057 $/kg	12,132
Total Operational Cost (C_{OMSB})		**43,455**

4.2.3 Optimizing the system

Optimization is done based on years of operation of this hybrid system. The solar fraction (F_S) as described in section 4.1.2 is varied from 0% to 20% and the best optimized system is obtained considering most economic solar biomass combination for an operational period of 10 years. The energy requirement, initial cost and the annual operational cost of the system are calculated as described in sections 4.1.4, 4.2.1 and 4.2.2, respectively.

The results are presented and elaborated in *Table 18* and *Figure 21*.

Table 18: *Main features of the system for various solar fractions*

Item	Solar Fraction				
	S_F = 0%	S_F = 5%	S_F = 10%	S_F = 15%	S_F = 20%
Solar collector/aperture area (m^2)	187	262	338	413	488
Boiler capacity (F & A Rating)/ (kg/h)	750	750	750	750	750
Annual energy demand/ (MJ/yr.)	2,801,587	2,801,587	2,801,587	2,801,587	2,801,587
Energy supply by solar system (MJ/yr.)	491,311	688,800	886,288	1,083,777	1,281,265
Energy supply by biomass boiler (MJ/yr.)	2,356,482	2,155,044	1,953,605	1,752,167	1,550,729
Annual biomass (Fuel) demand/(kg/yr.)	256,725	234,780	212,834	190,889	168,943
Initial cost of the system/$	125,930	145,292	164,655	184,017	203,379
Annual operational cost/ ($/yr.)	45,321	44,388	43,455	42,522	41,589

When the solar fraction is increased, the annual operational cost is decreased as the solar system gives more free energy to the system. But at higher solar fractions, capital investment is growing steadily due to the higher cost of the larger solar field. Even after 10 years of operation, the system alternatives with higher solar fraction show higher cost due to the high capital intensity of the solar field, as depicted in Figure 21. However, higher solar fractions show lower biomass (fuel) annual demand as shown in Figure 22.

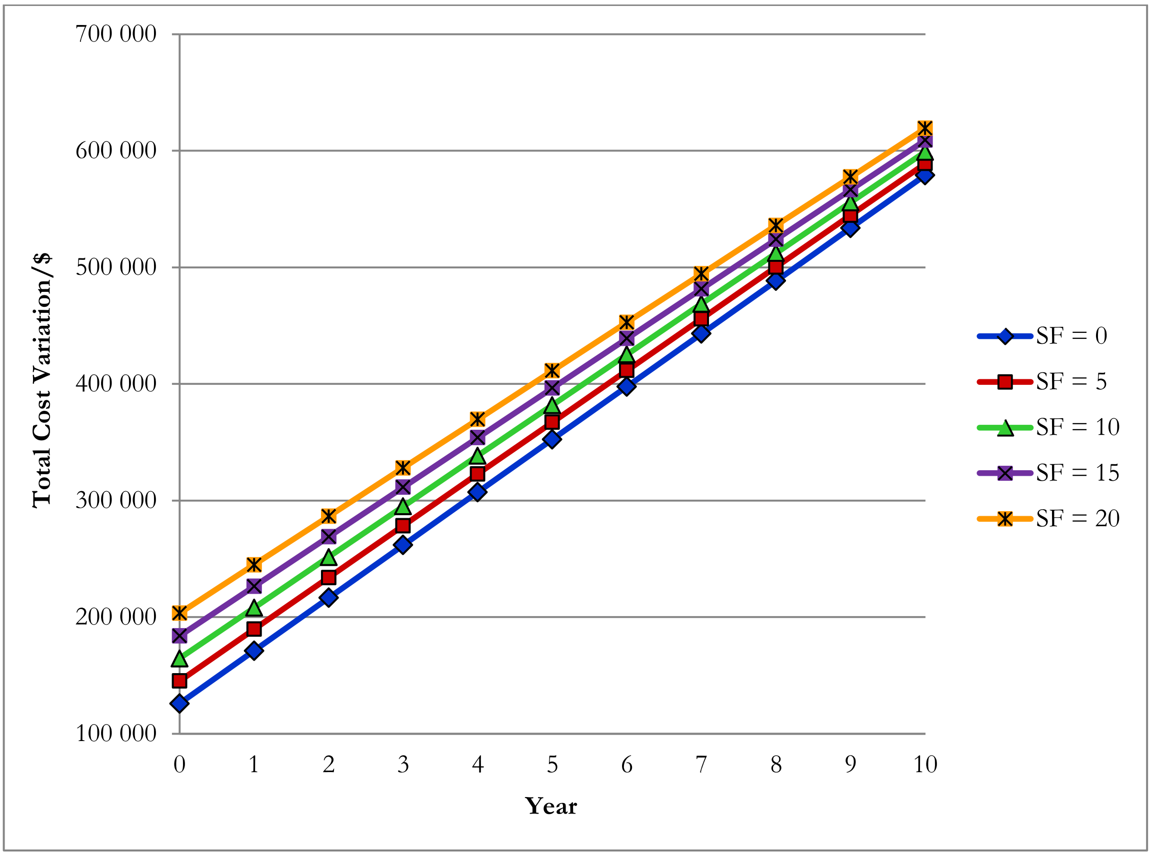


Figure 21: *Total cost (initial + operational) variation with time for different solar fraction (S_F) values*

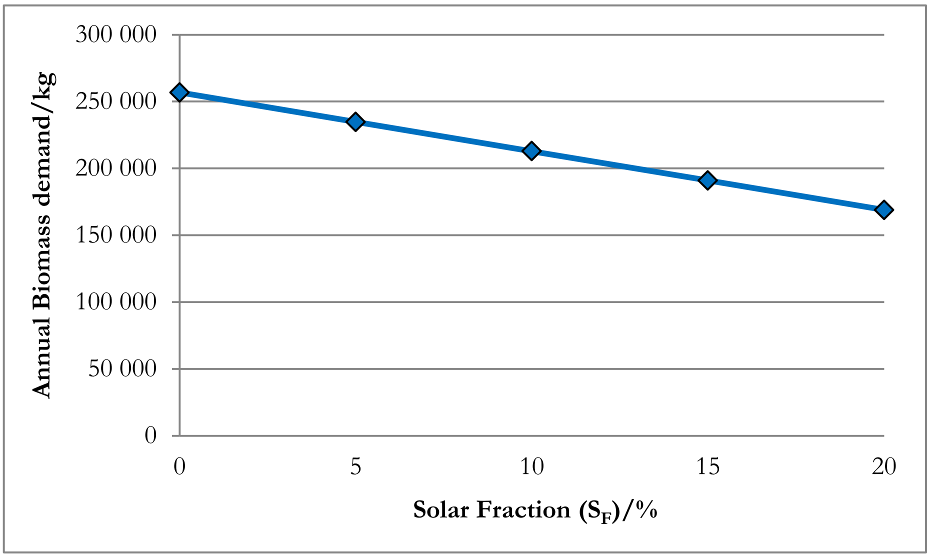


Figure 22: *Variation of annual biomass (fuel) demand with solar fraction*

4.3 FEASIBILITY ANALYSIS

4.3.1 Technical evaluation

Most of the technical findings related to the subject have been discussed above in Chapter 2-LITERATURE SURVEY, and throughout the report. Plenty of industrial biomass projects are in operation currently in the country and the biomass technology has becoming familiar to the industry. But the CSP is a completely new technology to the country, which needs to be explored. Introduction to this technology related to solar reflectors, absorber, secondary receiver, tracking system and efficiency is elaborated all the way through the report associated with technical feasibility. More detailed technological aspects like materials and their properties (e.g.: reflector material, absorber material), support structure of solar field, piping, valves and control system, etc., which are needed in the implementation process are not considered in detail as they are outside the scope of this project.

Overall efficiency throughout the year for the hybrid system can be expressed as,

$$\text{Overall efficiency} \quad = \frac{E_T}{\left(\frac{E_S}{\eta_{Solar}} + \frac{E_B}{\eta_{Boiler}}\right)}$$

Consider the same model calculations described in the section 4.1.4 for the system with solar fraction of 10%,

$$\text{Overall efficiency} \quad = \frac{2{,}801{,}587}{\left(\frac{886{,}288}{0.45} + \frac{1{,}953{,}605}{0.67}\right)}$$

Overall efficiency result = 57.3 %

However, if a higher solar contribution share is introduced by increasing the solar fraction, the overall efficiency is going to be reduced as the estimated efficiency of the solar field (45%) is lower than the estimated biomass boiler efficiency (67%). The relevant variation calculated by the BioSolar HeatApp simulator is given in Figure 23 below.

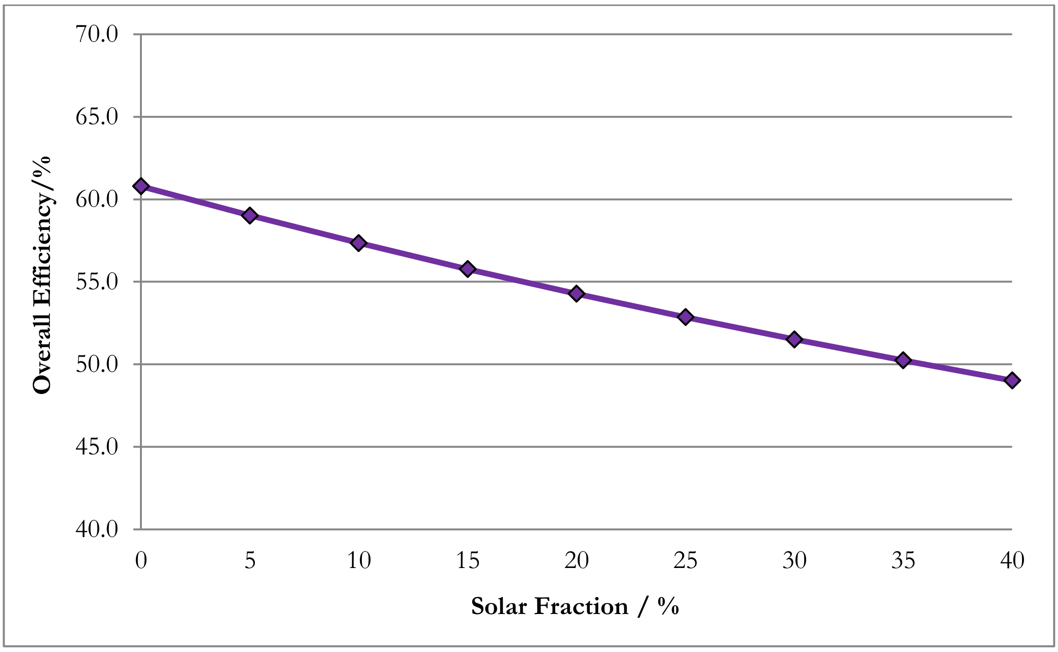


Figure 23: *Variation of overall efficiency of the hybrid system with solar fraction*

4.3.2 Financial evaluation

4.3.2.1 Life Cycle Cost analysis

The economic feasibility of the proposed hybrid system is evaluated comparing to a similar system that supplies process heat by fossil fuel fired (Diesel) boiler. The overall cost for boiler and installation are not commonly available for this kind of medium scale project but as per the current market prices, it can be assumed that the material and installation costs are 70% of those of the biomass project. For the comparison purposes, the additional equipment and piping cost is assumed to be same as the cost estimated for the biomass boiler described in *Table 16*. The other indirect cost is also assumed to be at the same level (20% of the investment) as described in section 4.2.1. These cost findings are given in Table 19.

Table 19: *Estimated initial cost for the system with a Diesel-fired boiler*

Description	**Rate**	**Cost/$**
Biomass boiler (material and installation cost)	\$ 54,000 × 0.7/(1 tone boiler)	37,800
Additional piping and equipment		10,800
Other (Indirect cost, Contingencies)	20% of investment	9,720
Total Capital Cost (C_{IND}) – Diesel-fired boiler		**58,320**

The cost of operational staff will be more critical than the cost of maintenance of plant and equipment for this kind of medium scale project as described in section 4.2.2. For this cost estimation, it is assumed that 1 supervisor (skilled labour) and 4 technicians (semi-skilled) are engaged in this O & M works of the diesel boiler system. Thus the O & M cost can be roughly accounted as 30% of the boiler cost. The insurance cost is assumed to be 1% of the investment, i.e. the same as in hybrid system calculations, for comparison reasons.

The calculation of annual fuel (diesel) cost is as follows:

The annual average occupancy R_G = 65 %

Total maximum daily energy requirement (ME_S) = 11,809 MJ/day (section 4.1.1)

Annual energy supply by diesel boiler = 11,809 × 0.65 × 365

= 2,801,587 MJ/yr.

The overall efficiency of the boiler throughout the year (η_D) = 72% (Winkel, 2010)

So that, Annual diesel fuel consumption is given by

$$M_{DSL} = \frac{2{,}801{,}587}{\eta_D \times LHV}$$

LHV of diesel is taken as 42.0 MJ/kg (UNDP, 2013)

Then, M_{DSL} = 2,801,587/ (0.72 × 42)

= 92,645 kg/yr.

Cost of the diesel is assumed to be 0.714 $/kg referring to the present market values (transport and storage costs are included).

Annual cost of fuel supply = 92,645 × 0.714

= 66,175 $/year

Considering above statements, the total annual operational cost for a system with diesel boiler is summarized in Table 20.

Table 20: *Estimated annual operational cost for a system with diesel boiler*

Description	**Rate**	**Cost/($/yr.)**
O & M	30% of boiler and installation cost.	17,496
Insurance	1% of the investment	583
Fuel (Diesel)	0.714 $/kg	66,175
Total Operational Cost (C_{OMD}) – Diesel-fired boiler		**84,254**

Comparison of total costs between diesel boiler system and hybrid system with low solar fractions (S_F = 0%, 5% and 10%) for a period of 10 years are obtained and presented below in Table 21.

Table 21: *Total cost variation with time for hybrid system and for diesel boiler system*

Year	**Total cost/$**			
	Solar-Biomass Hybrid System			**Diesel System**
	S_F = 0	**S_F = 5**	**S_F = 10**	
0	125,930	145,292	164,655	58,320
1	171,251	189,680	208,110	142,574
2	216,573	234,069	251,565	226,829
3	261,894	278,457	295,020	311,083
4	307,215	322,845	338,475	395,337
5	352,537	367,233	381,930	479,591
6	397,858	411,622	425,385	563,846
7	443,180	456,010	468,840	648,100
8	488,501	500,398	512,295	732,354
9	533,823	544,787	555,751	816,608
10	579,144	589,175	599,206	900,863

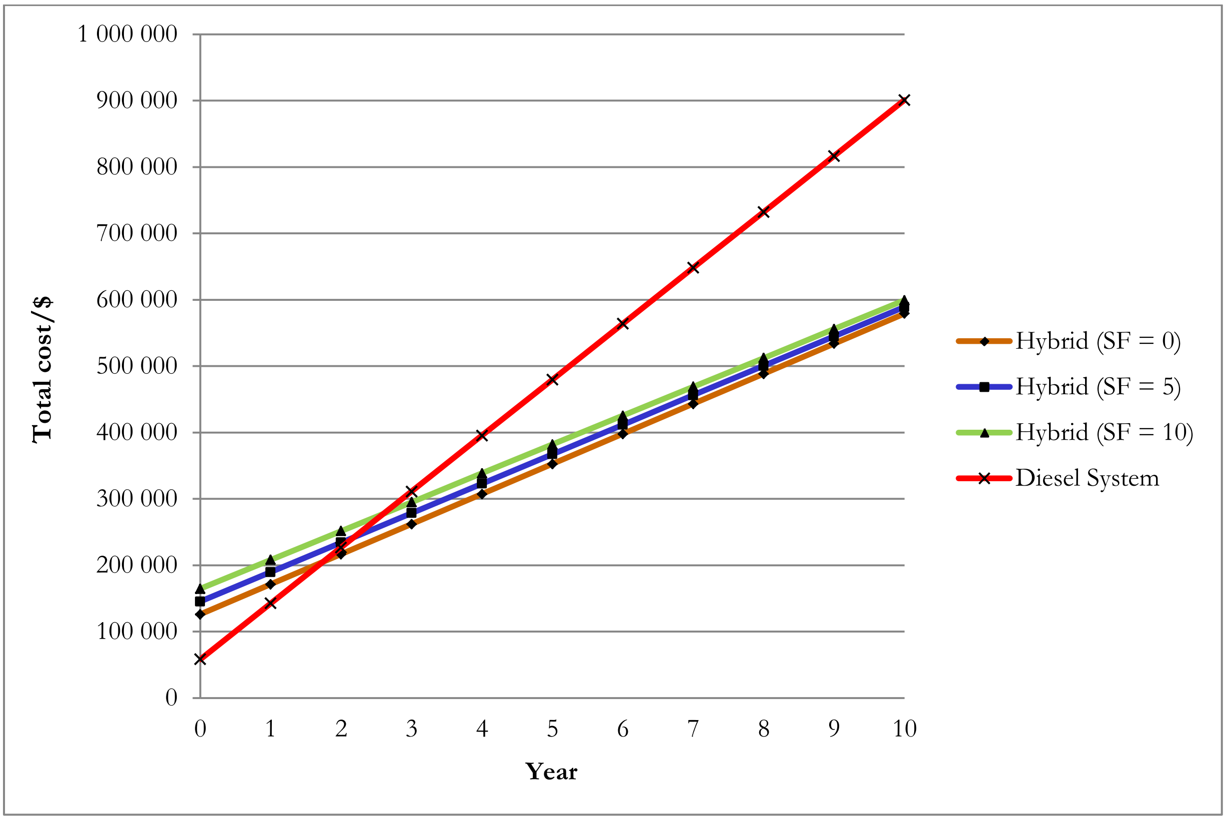


Figure 24: *Comparison of total cost variation with time for hybrid system and diesel boiler system*

4.3.2.2 Simple Payback period (SPP)

Simple payback period can be expressed for two alternative energy projects as,

$$\text{SPP} = \frac{Net\ Investment}{Net\ Annual\ Cost\ Saving}$$ (Sri Lanka Energy Managers Association, 2000)

Then the SPP for hybrid system with solar fraction 10% and diesel boiler system can be given by,

$$\text{SPP} = \frac{C_{ISB} - C_{ID}}{C_{OMD} - C_{OMSB}}$$

$$= (164{,}655 - 58{,}320) \Big/ (84{,}254 - 43{,}455)$$

<u>SPP = 4.1 years</u>

Simple payback period is further reduced when the actual annual average occupancy ratio of the hotel is at a higher value than estimated (65%). For example, for an annual R_G of 75% (if the same solar-biomass combination (S_F=10%) is maintained), the **SPP becomes 2.9 years!**

4.3.2.3 Return on Investment (ROI)

Return on investment can be expressed for two alternative energy projects as,

$$\text{ROI} = \frac{Net\ Annual\ Cost\ Saving}{Net\ Investment} \times 100\ \%$$ (Sri Lanka Energy Managers Association, 2000)

Then the ROI for the hybrid system with solar fraction 10% and for the diesel boiler system can be given by,

$$\text{ROI} = \frac{C_{ISB} - C_{ID}}{C_{OMD} - C_{OMSB}} \times 100\ \%$$

$$= (84{,}254 - 43{,}455) \Big/ (164{,}655 - 58{,}320) \times 100\ \%$$

<u>ROI = 38 %</u>

Return on investment is further increased when the actual annual average occupancy ratio of the hotel is at a higher value than estimated (65%). For example, for an annual R_G of 75% (if the same solar-biomass combination (S_F=10%) is maintained), the **ROI becomes as high as 45 %!**

4.3.3 Environmental evaluation

As described in section 2.2.1, biomass can be taken as carbon neutral over the entire lifespan of the fuel (from growing stage to burning stage). Also, it brings a clear solution by reducing other greenhouse gases like SO_2, NO_2, etc. Relevant comparison with fossil fuel is given in *Table 22*.

***Table 22**: Net life cycle emission of CO_2, SO_2 and NO_X for electricity generation*
(Boyle, 2004)

Fuel Type	Emission/ (g/kWh)		
	CO_2	SO_2	NOx
Straw (Combustion)	13	0.88	1.55
Forestry residues (Combustion)	29	0.11	1.95
Energy crops (Gasification)	14	0.06	0.43
Forestry residues (Gasification)	24	0.06	0.57
Natural Gas	446	0.0	0.5
Coal	955 - 987	1.5 – 11.8	2.9 – 4.3

CO_2 emission coefficient by diesel = 10.16 kg CO_2/gallon (U.S. Department of Energy)
= 2.684 kg CO_2/liter
= 2.233 kg CO_2/kg diesel
(Density of diesel is taken as 0.832 kg/liter)

Annual CO_2 Emission reduction = $M_{DSL} \times 2.233$
= $92,645 \times 2.233$
= 206,884 kg CO_2/yr.

Annual CO_2 Emission reduction = 206.9 tCO_2/yr.

4.3.4 Social evaluation

Social benefits can be explained comparative with the number of employment opportunities that can be additionally generated for the community due to the hybrid system implementation. Especially in the biomass supply chain, considerable employment opportunities are produced proximate to the site location area, which can then be reflected as "Rural Development".

Energy crop (Gliricidia) can produce approximately 20 tonnes of biomass fuel per hectare per year (Sustainable Energy Authority) while there are two employment openings per hectare that can be generated in connection with biomass supply including farming, harvesting, pre-processing and transportation (Nixon J.D., 2012).

If the same combination used in the model calculations with 10% solar fraction (S_F = 10%) is considered,

Annual biomass demand (M_{BIO})	= 212,834 kg/yr.
Annual yield	= 20 t/ha/yr. (Sustainable Energy Authority)
Land reservation (assuming mono-crop)	$= {(212{,}834)}/{(20{,}000)}$
	= 10.5 ha
Specific Employment generation	= 2 persons/ha (Nixon J.D., 2012)
Total employment produced in biomass supply	$= 10.5 \times 2$
	= **21 persons**.

The hybrid system with solar fraction of 10% can therefore produce **21 no. of employment** (labour) offerings related to the biomass fuel supply chain for the considered medium-scale hotel demand. When solar fraction is further lowered, more biomass supply is required and more employment is generated. But the consistency of supply chain has to be considered.

Employment engaged in O & M works in the biomass boiler is not considered as approximately the same number can be employed when considering a fossil fuel (diesel) boiler. But the employment generated in the solar field O & M works can be taken as additional and it is accounted to **5 technicians** as described in section 4.2.2.

5 DISCUSSION

This solar-biomass hybrid concept mitigates the weaknesses associated with these renewable technologies when employed individually. Biomass makes the energy supply consistent irrespective to the variation in solar energy due to the seasonal and climatic effects. Furthermore, engagement of solar energy reduces biomass demand thus reducing the risk of uncertainty associated with the biomass supply chain.

Optimized combination of this hybrid system was discussed by introducing a factor called "solar fraction". The operational cost is lower at higher solar fraction but the results show that even after 10 years or operation the systems with higher solar fraction show higher costs due to their high capital cost. The most economical systems alternatives are at lower solar fractions but the annual biomass fuel demand is higher at lower solar fractions. Likewise, a purely biomass-fired system alternative is not preferred as it reduces the energy security and increases the dependency on one single technology.

Plenty of industrial biomass projects are in operation currently in Sri Lanka and the biomass technology is becoming familiar in the industrial applications. But the CSP is a new technology to the country which needs to be explored, especially when employed for thermal energy supply. As a rule of thumb it would be required to receive 1,800 kWh/m^2 or more annual DNI to make a project viable for power generation. Dry zone in Sri Lanka receives annual DNI in the range of 1,500 kWh/m^2 and some locations show 1650 kWh/m^2 of annual DNI. The values are slightly lower than the benchmark of power generation but it would still be feasible to implement for direct heat applications with simplified and cheaper Linear Fresnel technology as described in this study. Meanwhile, higher effectiveness can be achieved with this technology having north-south orientation of its single axis tracking system as the country is situated near the equator.

High capital cost of renewable energy projects is a common constraint towards the wider deployment of sustainable solutions. However, promoting renewable energy in a developing country relates to various human development factors, including the expansion of ecological sustainability, competitiveness and security of energy supply. Referring to this fact, the Ministry of Power and Energy in Sri Lanka encourages the private sector to develop small non-conventional renewable energy projects that generate electricity by introducing a "Feed-in-tariff" policy. This has been a success story within few years by adding considerable contribution to the national grid supply through many such small-scale projects. But there is no such tool in practice to promote direct heat applications like process heat or indirect applications of thermal energy like absorption refrigeration projects driven by renewable sources.

Solar field cost is estimated at 165 $\$/m^2$ taken from data with Indian practices which is further an optimistic value for the estimations in Sri Lankan projects. This high capital investment is a main barrier to practical solar projects. To overcome this issue, granting of soft loan at lower interest rates to the project promoters can be suggested. This can be achieved by treating positively at the energy policy level the feasibility aspects of added national grid security, energy conservation or imported fuel cost savings, environmental benefits and social benefits in the country.

6 CONCLUSION

The proposed solar biomass hybrid system was considered to be implemented for covering the process heat requirements in a medium-scale hotel with about 200 guests capacity and estimated annual average guest occupancy of 65%. The advantages and relevant characteristics were analyzed through the areas of technical, financial, environmental and social evaluation.

Biomass technology has become proven and successful in industrial applications once the biomass supply chain is properly managed. Concentrated Solar Power (CSP) technology is a new technology to the country of Sri Lanka, but the technique can be implemented starting with simpler technological solutions like Linear Fresnel modules for process heat supply, as proposed in this study. The main system components like collector, receiver, absorber, supporting structure and the tracking devices would not be impossible to implement in a real application with the available technology in the country. The overall efficiency of this hybrid system varies around 50% to 60% which can be considered as in an acceptable range.

Normally, the renewable energy conversion projects are capital intensive but the simple payback period (SPP) of the hereby evaluated hybrid system is obtained within 3-4 years when compared to a regular fossil fuel (diesel) boiler system. This SPP is further reduced when the actual annual average occupancy ratio of the hotel is at a higher value than initially estimated (65%). For example, for annual R_G of 75% (if the same solar-biomass combination (S_F=10%) is maintained), the SPP decreases to 2.9 years. Also, the annual operational cost savings are accounted at around $ 40,000.

The total annual CO_2 saving is accounted as 207 tons compared to a total fossil fuel (diesel) fired boiler system. This hybrid system can generate additional 26 employment opportunities in the proximity of the site location area, including the establishment of a local biomass supply chain and the maintenance demand of the system. This offers a clear chance for a valued support towards the rural development in the country.

Therefore, the proposed solar-biomass hybrid system can be considered as sustainable and non-conventional renewable energy establishment. Considering all of the above factors, this concept would be a feasible technology to implement in Sri Lanka for process heat applications.

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APPENDIX 1

"Bio Solar HeatApp"

Inputs

Hotel Data	Abbr	Value	Unit	Remarks
Guest capacity of the hotel (max)		200	Guests	
Estimated average annual occupancy ratio		65	%	
Minimum occupancy ratio		45	%	
Maximum occupancy ratio		100	%	Maximum at full capacity

Energy System Data	Abbr	Value	Unit	Remarks
Temperature of cold water supply (Average ambient temp)	T_c	28	^{0}C	
Specific enthalpy of cold water supply		117	kJ/kg	
Daily hot water consumption for bath & shower per guest		25	l/day	
Daily hot water consumption for kitchen, restaurant and dining (per guest)		20	l/day	
Hot water storage temperature		60	^{0}C	
Enthalpy of hot water @ storage temp		251	kJ/kg	
Pressure of laundry steam supply		8	bar	
Specific enthalpy of dry sat. steam @ supply pressure	h_g	2774	kJ/kg	

Solar Data of the location	Abbr	Value	Unit	Remarks
Annual Average DNI		1620	kWh/m^2/yr	
Minimum daily DNI		0	kWh/m^2/yr	
Maximum Daily DNI		1944	kWh/m^2/yr	

Biomass and boiler Data	Abbr	Value	Unit	Remarks
Calorific Value of fuel		13.7	MJ/kg	
Cost of fuel		0.057	$/kg	
Rated Efficiency of boiler		72	%	
Annual overall efficiency		67	%	

Input	Output

Maximum Energy Calculation

Hot water quantity requirement (max)

Daily hot water requirement for bath & shower per guest (@ storage temp.)		25.00	L
Daily hot water requirement for other uses per guest (@ storage temp.)		20.00	L
Total daily hot water requirement per guest (@ storage temp.)		**45.00**	**L**
Total daily maximum hot water requirement in hotel		**9000**	**L**
Energy requirement for hot water			
Temperature of cold water supply (Average ambient temp)	T_C	28	^0C
Hot water storage temperature	T_S	60	^0C
Assume density of hot water		1	kg/L
Assume heat capacity of water	C_P	4.2	kJ/(kg.K)
Maximum daily heat energy requirement for hot water	=	M_{HW}.C. (T_{HW}-Tcs)	
		1210	MJ/Day
Allow 8% losses (line and storage losses)		-	-
Maximum daily heat energy requirement for hot water		**1,306**	**MJ/Day**
Amounts of daily steam requirements			
Daily steam consumption per guest		20	kg/day
Total maximum steam consumption in the hotel per day		4000	kg/day
Energy requirement for steam supply			
Specific enthalpy of dry sat. steam @ supply pressure		2774	kJ/kg
Maximum energy input to the laundry		11,096	MJ/day
Allow 3% losses			
Actual energy input to the laundry		11,429	MJ/day

Condensate mass recovery from the indirect heating (including losses)		57	%
Mass on return		2,280	kg/day
Specific enthaphy of saturated water @ condensate pressure		419	kJ/kg
Heat content of the condensate		955	MJ/day
Allow 3% line losses			
Heat recovery from condensate		**927**	**MJ/day**
Maximum daily energy requirement in the steam supply		10,502	MJ/day
Maximum daily energy requirement in the steam supply		**10,502**	**MJ/day**
Total maximum daily energy requirement		**11,809**	**MJ/day**

Solar System design

Input

Maximum daily heat energy requirement for hot water		1,306	MJ/Day
Maximum daily energy requirement in the steam supply		10,502	MJ/Day
Maximum steam supply contribution from solar system in maximum occupied day (Solar fraction)	F_S	10	%
Maximum daily energy supply by solar system		2,357	MJ/Day
Allow 3% losses			
Maximum daily energy supply by solar system		**2427**	**MJ/Day**
Annual DNI		1620	kWh/m^2
Daily Average DNI		4.44	kWh/m^2
		15.978	MJ/m^2
Overall efficiency of the solar system		45.0	%
Collector area requirement		**338**	**m^2**
Space utilization factor		3	
Total rooftop area requirement		**1,013**	**m^2**

Solar System design

Input

Maximum daily heat energy requirement for hot water		1,306	MJ/Day
Maximum daily energy requirement in the steam supply		10,502	MJ/Day
Maximum steam supply contribution from solar system in maximum occupied day (Solar fraction)	F_S	0	%
Maximum daily energy supply by solar system		1,306	MJ/Day
Allow 3% losses			
Maximum daily energy supply by solar system		**1346**	**MJ/Day**

Annual DNI		1620	kWh/m^2
Daily Average DNI		4.44	kWh/m^2
		15.978	MJ/m^2
Overall efficiency of the solar system		45.0	%
Collector area requirement		**187**	**m^2**
Space utilization factor		3	
Total rooftop area requirement		**561**	**m^2**

Solar System design

Input

Maximum daily heat energy requirement for hot water		1,306	MJ/Day
Maximum daily energy requirement in the steam supply		10,502	MJ/Day
Maximum steam supply contribution from solar system in maximum occupied day (Solar fraction)	F_S	20	%
Maximum daily energy supply by solar system		3,407	MJ/Day
Allow 3% losses			
Maximum daily energy supply by solar system		**3509**	**MJ/Day**
Annual DNI		1620	kWh/m^2
Daily Average DNI		4.44	kWh/m^2
		15.978	MJ/m^2
Overall efficiency of the solar system		45.0	%
Collector area requirement		**488**	**m^2**
Space utilization factor		3	
Total rooftop area requirement		**1,464**	**m^2**

Input	Output

Case Analysis (Daily variations)

Occupancy ratio of the day	R_G	90	%
Solar radiation of the day	DNI_D	2.00	kWh/m^2
		7.20	MJ/m^2
Amount of hot water requirement		8100	L/day
Energy requirement for hot water		**1,176**	**MJ/day**
Amount of Steam requirement to laundry		**3600**	**kg/day**
Actual Energy requirement for steam		**9,452**	**MJ/day**
Heat content of condensate recovery from laundry		**817**	**MJ/day**
Condensate mass on return after laundry		**2,052**	**kg/day**
Total daily Energy requirement		**10,628**	**MJ/day**

Case 1 : Low solar day (Solar energy is not enough to satisfy hot water requirement)

Total energy generated by solar system	1094	MJ/day
Case-1 analysis ?	1	*1-Yes, 0-No*

Hot water system

Energy supply by solar to hot water system		1094	MJ/day
Energy requirement by biomass boiler to hot water generation		82.0	MJ/day
Allow 5% losses			
Energy supply by biomass boiler to hot water generation		86.1	MJ/day
Specific enthalphy of dry sat. steam @ supply pressure		2774	kJ/kg
Condensate return pressure		0.50	barg
Specific enthalphy of condensate		468	kJ/kg
Temperature @ condensate		112	C
Energy supply by 1 kg of steam		2306	kJ/kg
Steam mass supply to hot water heating		**37.3**	**kg/day**
Amount of flash steam generation @ ambient pressure per 1kg of condensate @ 0.5 barg	X	0.022	
Amount of flash steam generation		0.81	kg/day
Enthalpy of evaporation		2257	kJ/kg
Energy recovered by flash steam generation		**1.83**	**MJ/day**

Steam system

Amount of Steam requirement to laundry		3,600	kg/day
Amount of Steam requirement to hot water heating		37.3	kg/day
Total steam generation		3,637	kg/day
Condensate mass recovery after hot water heating		37.3	kg/day
Condensate mass on return after laundry		2,052	kg/day
Total mass on return to feed water tank		2,089	kg/day
Makeup cold water supply to feed water tank		1,548	kg/day
Boiler feed water temperature		**69.5**	**^{0}C**

Input	Output

Case Analysis (Daily variations)

Occupancy ratio of the day	R_G	90	%
Solar radiation of the day	DNI_D	5.00	kWh/m^2
		18.00	MJ/m^2
Amount of hot water requirement		8100	L/day
Energy requirement for hot water		**1,176**	**MJ/day**
Amount of Steam requirement to laundry		**3600**	**kg/day**
Actual Energy requirement for steam		**9,452**	**MJ/day**
Heat content of condensate recovery from laundry		**817**	**MJ/day**
Condensate mass on return after laundry		**2,052**	**kg/day**
Total daily Energy requirement		**10,628**	**MJ/day**

Case 1 : Low solar day (Solar energy is not enough to satisfy hot water requirement)

Total energy generated by solar system	2734	MJ/day
Case-1 analysis ?	0	*1-Yes, 0-No*

Hot water system

Energy supply by solar to hot water system		0	MJ/day
Energy requirement by biomass boiler to hot water generation		0.0	MJ/day

Allow 5% losses			
Energy supply by biomass boiler to hot water generation		0.0	MJ/day
Specific enthalphy of dry sat. steam @ supply pressure		2774	kJ/kg
Condensate return pressure		0.50	barg
Specific enthalphy of condensate		468	kJ/kg
Temperature @ condensate		112	C
Energy supply by 1 kg of steam		2306	kJ/kg
Steam mass supply to hot water heating		**0.0**	**kg/day**
Amount of flash steam generation @ ambient pressure per 1kg of condensate @ 0.5 barg	X	0.022	
Amount of flash steam generation		0.00	kg/day
Enthalpy of evaporation		2257	kJ/kg
Energy recovered by flash steam generation		**0.00**	**MJ/day**

Steam system

Amount of Steam requirement to laundry		3,600	kg/day
Amount of Steam requirement to hot water heating		0.0	kg/day
Total steam generation		3,600	kg/day
Condensate mass recovery after hot water heating		0.0	kg/day
Condensate mass on return after laundry		2,052	kg/day
Total mass on return to feed water tank		2,052	kg/day
Makeup cold water supply to feed water tank		1,548	kg/day
Boiler feed water temperature		**0.0**	**^{0}C**

Case 2 : High solar day (Solar energy satisfies hot water requirement and generates steam)

Total energy generated by solar system		**2734**	**MJ/day**
Case-2 analysis ?		1	*1-Yes, 0-No*
Energy supply by solar system to hot water system		1176	MJ/day
Allow 2% losses			
Actual Energy supply by solar system to hot water system		1176	MJ/day
Energy supply by solar to steam generation		1,559	MJ/day
Allow 2% losses			

Energy received to steam generation by soalr system		1,528	MJ/day
Energy received to steam generation by biomass boiler		7,893	MJ/day
Allow 2% losses			
Energy supply by biomass boiler to steam generation		**8,051**	**MJ/day**
Solar : Biomass, energy supply ratio to steam generation		16%	84%
Condensate mass on return after laundry		2,052	kg/day
Condensate mass return to solar steam generator		333	kg/day
Condensate mass return to boiler feed water tank		1,719	kg/day
Specific enthalphy of cold water supply		117	kJ/kg
Specific enthalphy of dry sat. steam @ supply pressure		2774	kJ/kg
Steam generation by solar system		613	kg/day
Steam generation by biomass boiler		2,987	kg/day
Cold water supply to feed water tank		1,268	kg/day
Boiler feed water temperature		**69.4**	**^{0}C**

Input	Output

Case Analysis (Daily variations)

Occupancy ratio of the day	R_G	65	%
Solar radiation of the day	DNI_D	4.44	kWh/m^2
		15.98	MJ/m^2
Amount of hot water requirement		5850	L/day
Energy requirement for hot water		**849**	**MJ/day**
Amount of Steam requirement to laundry		**2600**	**kg/day**
Actual Energy requirement for steam		**6,826**	**MJ/day**
Heat content of condensate recovery from laundry		**590**	**MJ/day**
Condensate mass on return after laundry		**1,482**	**kg/day**
Total daily Energy requirement		**7,676**	**MJ/day**

Case 1 : Low solar day (Solar energy is not enough to satisfy hot water requirement)

Total energy generated by solar system	2428	MJ/day
Case-1 analysis ?	0	*1-Yes, 0-No*

Hot water system

Energy supply by solar to hot water system		0	MJ/day
Energy requirement by biomass boiler to hot water generation		0.0	MJ/day
Allow 5% losses			
Energy supply by biomass boiler to hot water generation		0.0	MJ/day
Specific enthalphy of dry sat. steam @ supply pressure		2774	kJ/kg
Condensate return pressure		0.50	barg
Specific enthalphy of condensate		468	kJ/kg
Temperature @ condensate		112	C
Energy supply by 1 kg of steam		2306	kJ/kg
Steam mass supply to hot water heating		**0.0**	**kg/day**
Amount of flash steam generation @ ambient pressure per 1kg of condensate @ 0.5 barg	X	0.022	
Amount of flash steam generation		0.00	kg/day
Enthalpy of evaporation		2257	kJ/kg
Energy recovered by flash steam generation		**0.00**	**MJ/day**

Steam system

Amount of Steam requirement to laundry		2,600	kg/day
Amount of Steam requirement to hot water heating		0.0	kg/day
Total steam generation		2,600	kg/day
Condensate mass recovery after hot water heating		0.0	kg/day
Condensate mass on return after laundry		1,482	kg/day
Total mass on return to feed water tank		1,482	kg/day
Makeup cold water supply to feed water tank		1,118	kg/day
Boiler feed water temperature		**0.0**	**^{0}C**

Case 2 : High solar day (Solar energy satisfies hot water requirement and generates steam)

Total energy generated by solar system		**2428**	**MJ/day**
Case-2 analysis ?		1	*1-Yes, 0-No*
Energy supply by solar system to hot water system		849	MJ/day
Allow 2% losses			
Actual Energy supply by solar system to hot water system		849	MJ/day
Energy supply by solar to steam generation		1,579	MJ/day
Allow 2% losses			
Energy received to steam generation by soalr system		1,547	MJ/day
Energy received to steam generation by biomass boiler		5,247	MJ/day
Allow 2% losses			
Energy supply by biomass boiler to steam generation		**5,352**	**MJ/day**
Solar : Biomass, energy supply ratio to steam generation		23%	77%
Condensate mass on return after laundry		1,482	kg/day
Condensate mass return to solar steam generator		338	kg/day
Condensate mass return to boiler feed water tank		1,144	kg/day
Specific enthalphy of cold water supply		117	kJ/kg
Specific enthalphy of dry sat. steam @ supply pressure		2774	kJ/kg
Steam generation by solar system		621	kg/day
Steam generation by biomass boiler		1,979	kg/day
Cold water supply to feed water tank		835	kg/day
Boiler feed water temperature		**69.6**	**^{0}C**

Financial Analysis

1.Solar Biomass hybrid system

Estimated annual average R_G	65	%	Enter the values in case study page
Average Solar radiation (Annual)	4.44	kWh/ m^2	Enter the values in case study page

Initial Cost

Solar Field (material and installation cost)	165	$/m2	338	m^2	55,702	$
Additional piping and equipments					16,710	$
Biomass boiler (material and installation cost)	54000	$/(1 tone)			54,000	$
Additional piping and equipments					10,800	$
Other	20%				27,442	$
Total (Initial Cost)					**164,655**	**$**

Annual Operational Cost

O & M					29,677	$/year
Insurance					1,647	$/year
Fuel (biomass)	0.057	$/kg	212,834	kg	12,132	$/year
Total (annual operational)					**43,455**	**$/year**

2.Diesel Boiler system

Overall Boiler efficiency = 72 %

Initial Cost

Boiler (material and installation cost)		37,800	$
Additional piping and equipments		10,800	$
Other		9,720	$
Total		**58,320**	**$**

Annual Operational Cost

O & M					17,496	$/year
Insurance					583	$/year
Fuel (biomass)	0.714	$/kg	92,645	kg	66,175	$/year
Total					**84,254**	**$/year**

SPP	=	4.1	Years

ROI	=	38	%