

A hybrid solar
biomass power plant
environmental
sciences essay



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Abstract

Purpose Energy security is a major concern for India and many rural areas remain un-electrified. Thus, innovations in sustainable technologies to provide energy services are required. Biomass and solar energy in particular are resources that are widely available and underutilised in India. This paper provides an overview of a methodology that was adopted for designing and assessing the feasibility of a hybrid solar-biomass power plant in Gujarat.

Design/methodology/approach The methodology described is a combination of engineering and business management studies; the Analytical Hierarchy Process, for solar thermal technology selection; a cost-exergy approach, for design optimisation; Quality Function Deployment, for designing and evaluating a novel collector – termed the Elevation Linear Fresnel Reflector (ELFR); and case study simulations, for analysing alternative hybrid plant configurations.

Findings We recommended that for a hybrid plant in Gujarat, a Linear Fresnel Reflector of 14, 000 m² aperture is integrated with a 3 tonne biomass boiler, generating 815 MWh per annum of electricity for nearby villages and 12, 450 tonnes of ice per annum for local fisheries and food industries. However, at the expense of a 0.3 ¢/kWh increase in levelised energy costs, the ELFR can increase savings of biomass (100 t/a) and land (9 ha/a).

Research limitations/implications The research reviewed in this paper is primarily theoretical and further work will need to be undertaken to specify plant details such piping layout, pump sizing and structure, and assess plant performance during real operational conditions.

Originality/value We consider the methodology adopted proved to be a powerful tool for integrating technology selection, optimisation, design and

evaluation, and promotes interdisciplinary methods for improving sustainable engineering design and energy management. Keywords: Concentrating solar thermal power (CSP); linear Fresnel reflector (LFR); multi-criteria decision-making (MCDM); analytical hierarchy process (AHP); exergy.

1. Introduction

According to the 2011 census, 69% of India's population lived in the countryside and was sustained primarily by agriculture and small local industries (Census of India, 2011). As of 2008, 47.5% of India's population living in rural areas did not have access to electricity (Legros et al., 2009). Just fewer than 24,500 out of 112,401 villages in India without electricity were classified as being in remote and inaccessible areas (Nouni et al., 2009). The financial viability of extending the electricity grid to these areas is poor due to a dispersed population with a low peak power demand. Currently, the grid already suffers from high transmission and distribution losses, blackouts and power theft. Progress to improve access has been slow due to India's rapidly growing energy demand and population. On top of India's national energy problems, fossil fuel prices are rising globally and international pressure to use ever more sustainable energy sources is increasing, due to concerns about global warming. Thus, governments in India and the rest of the world have aims to increase the contribution of renewable energy sources to the total energy mix. As a result, organisations and researchers are constantly seeking to improve and develop innovative solutions of providing electricity and other energy services. India receives an abundance of solar energy: 4-7 kWh/m² per day. However, it is a resource

that is underutilised. India's grid-connected solar generation capacity in 2009 was a mere 2 MW (Buragohain et al., 2010). Therefore, in 2010, the Jawaharlal Nehru National Solar Mission was established to encourage growth in the solar energy sector in India. With the objective of establishing India as a global leader in solar energy, a number of targets have been specified; most notably, to achieve 20 GW of solar power by 2022 (Center for Climate and Energy Solutions, 2008). The first phase, up to 2013, of the Solar Mission aims to support off-grid systems, such as hybrid- Concentrating Solar thermal Power (CSP) plants generating electricity, heat and cooling, to empower people at the working class level (MNRE, 2010a, b). India's Solar Mission also proposed demonstration plants for Research and Development (R&D) into various CSP technologies, including 100–150 MW of solar hybridisation with coal, gas and biomass (Center for Climate and Energy Solutions, 2008). CSP technologies are currently expensive; thus the Indian government plans to provide support in the form of capital subsidies and soft loans. This is to help achieve grid parity by 2022, another objective of the Solar Mission (MNRE, 2010a). Solar thermal power plants would benefit from hybridisation with biomass due to the variable nature of solar energy, particular during the monsoon season in India. Biomass is a relatively cheap supplementary fuel to use and vast quantities are available in India – 370 million tonnes per year (Suresh, 2010). In India, a large proportion of biomass is generated as waste from agriculture and industries; by-products include husks, straws and stalks. Therefore the negative effects on land requirements from using biomass as a fuel can be avoided. Furthermore, around 15 – 30% of crop waste in India is currently burnt in open fields, which has severe health and environmental impacts (Venkataraman et al., <https://assignbuster.com/a-hybrid-solar-biomass-power-plant-environmental-sciences-essay/>

2006). There are numerous approaches to hybridising solar and biomass energy. Space heating systems naturally use solar energy but are often balanced with biomass to provide any additional heat required. The European project SOLLET (European network strategy for combined solar and wood pellet heating systems for decentralised applications) has installed 10 hybrid solar-biomass heating systems as demonstration plants across Europe. These test facilities vary in size and operate with different solar-pellet combinations (Chasapis et al., 2008). Another hybrid application, which is well documented in the literature, is the solar-biomass drier. Experimental studies of these hybrid types for the drying of agricultural products and foodstuffs have been performed in India, Thailand, and the Philippines (Bhattacharya et al., 2000; Sharma et al., 2009). Small biomass boilers have also been hybridised with solar hot water panels for domestic heating by a number of companies, including Solar Focus and Treco. One recent proposal for a hybrid solar-biomass power plant has been made by the Government of China which has apparently agreed a deal to buy 2 GW of solar thermal technology from eSolar to supplement a biomass driven generator (Fehrenbacher, 2010). Another power generating system, designed by Electricité de Marseille, claims to use solar thermal and biomass co-generation for district heating, and compressed air technology for producing electricity (Biopact, 2006). A hybrid system has even been used in the creation of diesel. New Mexico-based Sundrop Fuels have created a refinery that utilises CSP technology to heat the biomass in the process of creating a synthetic gas that can be formed into fuel. They assert that 30 percent of the necessary heat in this process will come from the CSP

technology, thus saving a third of the fuel that would have been required in <https://assignbuster.com/a-hybrid-solar-biomass-power-plant-environmental-sciences-essay/>

this process otherwise (Solar Thermal magazine, 2010). While there are many alternative approaches to hybridising solar and biomass, there is limited research on hybrid solar-biomass power plants. Solar thermal fieldBiomass-fired boilerSteam turbineAbsorption chillerElectricityIceReject heatFigure 1: The main components of a hybrid solar-biomass power plant for tri-generation. The solar thermal field, which contains multiple rows of solar thermal collectors (the CSP technology), and biomass-fired boiler both generate heat to convert water into steam. High pressure steam is sent to a turbine for electricity generation. Low pressure exhaust steam from the turbine can be utilised in an absorption chiller for cooling. Low grade reject heat may be used in additional thermal applications. A solar thermal field hybridised with a biomass-fired boiler for producing electricity, ice, and thermal energy, is of particular interest for India. A conceptual layout for a hybrid solar-biomass tri-generation plant is presented in Figure 1. During the day solar energy can be used to generate steam, and at night during cloudy periods waste biomass can be burnt as a supplementary fuel. Biomass boilers, steam turbines and chillers are well established technologies that are widely used in India. In contrast, electricity generation from solar thermal is a relatively new concept. The authors were therefore interested in investigating alternative solar thermal technologies for use in hybrid solar-biomass power in India. The aim of this paper is to provide an overview of the methodology that was adopted to evaluate the hybrid plant concept. The methodology had three specific objectives to achieve. Select a solar thermal collector technology for power generation in IndiaImprove selected solar thermal collector for applications in IndiaEvaluate the feasibility of hybrid solar-biomass power plants in IndiaThe paper initially outlines the developed <https://assignbuster.com/a-hybrid-solar-biomass-power-plant-environmental-sciences-essay/>

methodology. The individual studies carried out are then reviewed in response to the three aforementioned objectives. Publications by the authors arising from these studies are also reviewed. The effectiveness of the adopted methodology is discussed and the paper concludes with recommendations for further research on hybrid plants and future applications of the developed methodology.

2. Methodology

The methodology developed for designing and assessing the hybrid solar-biomass power plant involved several studies for technology selection, refinement and evaluation. The methodology steps are illustrated in Figure 2. Firstly, a literature review is carried out to identify and characterise the technology alternatives. Multi-criteria decision-making methods are utilised to preferentially rank the technology alternatives. Informed from the outcome of the AHP study, a technology is selected and its design improved. Alternative approaches to refine and improve the selected technology are sought, leading to the development of several design concepts. To evaluate the design concepts, Quality Function Deployment (QFD) is used to establish technical priorities and the Pugh selection matrix enables a weighted ranking of the concepts to be made. Case study simulations of the best design concepts are then used for a final evaluation and assessment. In this particular study, the linear Fresnel reflector was selected as a result of an Analytical Hierarchy Process (AHP) study. To improve the design, a techno-economic optimisation method was developed using the concept of cost and exergy. Novel design concepts were also developed to address the drawbacks of the LFR that were identified from the literature. The result of

the design improvement studies was two options for the hybrid plant: an optimised linear Fresnel reflector and a novel LFR variant, termed the Elevation Linear Fresnel Reflector (ELFR). Alternative case studies for a hybrid plant, including hybrid LFR- and ELFR- biomass power plants, were analysed using TRNSYS, a TRaNsient SYstem Simulation package. Literature review of solar thermal collectors Multi-criteria decision-making Design improvements Quality function deployment and Pugh matrix Case study simulations Alternatives Technology selection Design concepts Options for solar thermal field Figure 2: Methodology for assessing the feasibility of a hybrid solar-biomass power plant

3. Response to objectives

Objective 1: Select a solar thermal collector technology for power generation in India

To meet this objective a literature review of the primary concentrating solar thermal power technology options was performed, and is available from Ref. (Nixon et al., 2010). The review identified the main technology alternatives to be the Parabolic Trough Collector (PTC), Heliostat Field Collector (HFC), Linear Fresnel Reflector (LFR), Parabolic Dish Reflector (PDR) and Compound Parabolic Concentrator (CPC) with linear Fresnel lens. The review also encompassed alternative receiver-heat transfer fluid configurations, including synthetic oil, Direct Steam Generation (DSG), molten salt, air and the Stirling engine. As an output, the literature review revealed quantitative data for a series of technical, financial and environmental criteria (see Table 1). This gathered data provides researchers with all relevant data to compare CSP technologies for a specific application. Selecting the best solar

thermal technology for electricity generation in India is a complex decision as each technology has its own benefits and drawbacks. Solar thermal collectors comprise a concentrator (typically mirrors) tracking the sun with either a single-axis (linear collectors) or two-axis (point focusing collector) tracking mechanism to focus solar rays onto a target receiver. A heat transfer medium is usually passed through the receiver. The PTC (Figure 3a) is the most established technology but requires flexible high pressure pipe lines and expensive curved mirrors and evacuated tubes. The use of thermal oil as the heat transfer fluid also limits the maximum operating temperature. The HFC (Figure 3b) is a point focusing system that can produce high temperatures and conversion efficiencies. However, the HFC is expensive, as is the other point focusing system, the PDR (Figure 3c). The parabolic dish is typically combined with a sterling engine and has the highest solar to electricity conversion efficiency. The LFR (Figure 3d) is a relatively simple low cost collector but suffers from a low energy capture in comparison to other CSP technologies.

(b) Central receiver
Heliostats using 2-axis tracking
Solar rays
Absorbing pipe area
Glazing cover
Solar rays
Parabola aperture area

(a) Insulated absorbing pipe
Mirror elements
Solar rays

(d) Parabolic dish using two-axis tracking
Single point Receiver
Solar rays

(c) Figure 3a-d: Alternative solar thermal technologies: parabolic trough collector (a), heliostat field collector (b), parabolic dish reflector (c) and linear Fresnel reflector (d). Multi-Criteria Decision-Making (MCDM) tools enable a structured approach to be taken to analysing complex selection problems. They are particularly suited to multifaceted problems where there are both quantitative and qualitative data, as they can incorporate factual information and expert opinion into the decision rationale. They facilitate

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communication between relevant stakeholders in the decisions and use mathematics and psychology to provide a holistic approach to decision making, thus minimising the risk of a poor selection being made. There are numerous MCDM methods that have been use in a wide range of applications. A review of MCDM for sustainable energy planning is provided by Pohekar and Ramachandran (Pohekar and Ramachandran, 2004). Higgs (Higgs, 2006) reviews MCDM techniques combined with Geographical Information Systems for locating waste facilities. The Analytical Hierarchy Process was developed by Thomas. L. Saaty (Saaty, 1980) and is the most favoured of all MCDM techniques, however, its use has been relatively neglected in the field of solar thermal. To select a CSP technology for electricity generation in Gujarat the AHP method was adopted. The quantitative data from the literature review (Table 1) fed into the AHP and qualitative data was gathered through a workshop, consisting of a panel convened at the Solar Energy Centre in Delhi, India, to obtain experts' opinions. The results from the AHP study are shown in Figure 4, and indicate the preferred solar thermal technology option for Gujarat to be the linear Fresnel lens or reflector type collector. For the full AHP study the reader is referred again to Ref. (Nixon et al., 2010). Figure 4: Preferential range of rankings for CSP technologies for electricity generation in Gujarat, India [from (Nixon et al., 2010)].

Objective 2: Improve selected solar thermal collector for applications in India

Provisional work was undertaken by the authors to further investigate the Fresnel lens-CPC and LFR technologies. Several prototype collectors where

designed and constructed at Industrial Boilers Ltd, Gujarat, and the Indian Institute of Technology (IIT), Delhi. Even though the Fresnel lens-CPC technology was indicated as one of the preferred solar collectors for India, at an early stage it became evident that in-house manufacturing constraints restricted further development of the technology. The authors were keen to source or manufacture components locally, thus avoiding expensive imports; however Fresnel lenses require high precision optical surface generation facilities that were unavailable. Therefore, the decision was made to focus on R&D for the LFR. One particular disadvantage of the LFR is a low annual optical efficiency, due to shading and blocking caused by adjacent rows. Subsequently, a method was sought to optimise the LFR mirror spacing arrangement. Building upon the work of Mathur et al. (Mathur et al., 1991), a cost-exergy optimisation approach was developed to maximise the LFR's exergy and operational hours, and minimise capital costs. The detailed study relating to this design method can be found in Ref. (Nixon and Davies, 2012). The cost exergy method is based on the optical modelling of a series of alternative mirror spacing arrangements by means of ray-tracing to determine an incident angle dependant optical efficiency. This enables the annual performance for different mirror spacing arrangements to be estimated for a Typical Meteorological Year (TMY). The approach also enables the ideal operating temperature of the collector to be indicated. For a prototype LFR collector developed in Vapi, Gujarat, (see Figure 5) the cost-exergy optimisation indicated an ideal operating temperature of 300 °C and a mirror arrangement spaced for the onset of shadowing to occur at a solar profile angle of 45°. In comparison to Mathur's conventional method for specifying the mirror spacing arrangement in an LFR system, the cost-exergy

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method increased annual exergy by 9% with an additional 122 operational hours per annum predicted. Though the method optimises mirror spacing design according to site location and application, the LFR still remains to have less energy capture than other CSP technologies. It was therefore of interest to seek further improvements to the LFR, particularly since its design has remained relatively unchanged since its conception in 1957. C: Local My DocumentsPicturesGujarat LFRP2182335. JPG

Figure 5: An LFR prototype developed in Vapi, India. Through the development and application of a multi-criteria decision-making methodology comprising AHP, Quality Function Deployment (QFD) and Pugh selection matrix, a number of novel LFR design were evaluated. Extracting the customer requirements for a collector in India from the AHP results, design priorities for a novel solar thermal collector were established using QFD's house of quality. Selection of the best concept was then made using a Pugh selection matrix to make a weighed judgement based on the design priorities. The methodology is described in detail in Ref. (Nixon et al., 2013). Consequently, an Elevation LFR design was chosen where the mirror elements rise to remove shadowing and blocking of reflected rays throughout the day. A prototype of the collector was built at Aston University and is shown in Figure 6. To validate the selected concept a detailed technical and financial analysis was performed to compare the ELFR to a conventional LFR. It can be estimated that the ELFR increases annual exergy, optical efficiency, operational hours and capital cost by 13–23%, 9–25%, 9–24% and 16–28% respectively. The details of this study are also in Ref. (Nixon et al., 2013). In comparison to a conventional LFR, the ELFR was found to reduce land usage by as much as 17%. It was concluded that the ELFR is particular suited for applications with low land availability and high

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land costs, and the methodology outlined has a wider potential for future design and decision activities in the field of solar thermal and renewable energy. Figure 6: Prototype Elevation Linear Fresnel Reflector constructed on roof of Aston University, UK. C: Documents and Settings\sixonjd1\Desktop\Collector pictures\DSC_0192.JPG: Documents and Settings\sixonjd1\Desktop\Collector pictures\DSC_0047.JPG

Objective 3: Evaluate the feasibility of hybrid solar-biomass power plants in India

To evaluate hybrid LFR- and ELFR-biomass power plants for tri-generation in Gujarat, two case study models were developed in TRNSYS. The case study models were specified accordingly for a 5 MW thermal power plant. Details of the model can be found in Ref. (Nixon et al., 2012). The case studies were evaluated by reviewing a series of technical, financial and environmental considerations for varying plant solar multiples. This included energy efficiency (η_I), exergetic efficiency (η_{II}) and cost per exergy loss (C_{pel}) for the collector (c), boiler (b), heat cycle (hc) and overall system (os); levelised cost of electricity (LCOE); levelised energy cost (LEC); payback period on total capital cost (PPcap); payback period on solar field (PPsol); mass of biomass saved (Bsaved), and resulting land saved (Lsaved). The solar multiple is a ratio of the energy provided by the solar field to the rated capacity of the prime mover or power block. For a solar multiple of 1, the solar field at a peak design irradiance value would be able to drive the prime mover at full load. Results for the two Gujarat case study plants are presented in Figures 7a-d and 8a-d. For the LFR-biomass power plant, a solar field of 9350 m², costing 165 \$/m², was required to result in a solar multiple

of 1. The model parameters for the Gujarat ELFR plant were the same as those in case study 1, except that the ELFR technology was utilised.

Therefore, a smaller sized solar field aperture area, 9000 m², achieved a solar multiple 1. Based on the ELFR's capital cost increase in comparison to a typical LFR, 16-28%, a value of 200 \$/m² was assumed for the solar field.

Figure 6a-d: Gujarat pilot plant (case study 1) shows: (a) the minimum energy and exergetic efficiencies occur at the heat cycle, and the overall system energy and exergetic efficiencies decrease relatively constantly from 0.067 to 0.042 and 0.056 to 0.040 for SM = 0-2; (b) the overall system cost per exergy loss increases by hybridising with solar, but remains relatively constant for larger SMs; (c) the levelised costs of electricity and energy remains relatively constant among the SM alternatives, around 72 and 22 ¢/kWh respectively, and a solar multiple of 1-1.5 results in the minimum payback period for the solar investment (33 years) and a capital cost payback period of 34-39 years; (d) the biomass and land saving becomes less substantial for SM > 1, at SM = 1 the hybrid plant saves 1800 tonnes and 140 hectares per annum. [1][1] Reprinted from Energy, Vol

46, Issue 1, J. D. Nixon, P. K. Dey and P. A. Davies, The feasibility of hybrid solar-biomass power plants in India, Pages 541-554., Copyright (2012), with permission from Elsevier. Figure 8a-d: Gujarat ELFR plant (case study 2)

shows: (a) the minimum energy and exergetic efficiencies occurred at the heat cycle, and the overall system energy and exergetic efficiencies decreased relatively constantly from 0.067 to 0.043 and 0.056 to 0.042 for SM = 0 - 2; (b) the overall system cost per exergy loss increased by

hybridising with solar, but remained relatively constant for larger SMs; (c)

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among the SM alternatives, around 73 and 23 ¢/kWh respectively, and a solar multiple of 1 resulted in the minimum payback period for the solar investment (33 years) and a capital cost payback period of 35 years; (d) the biomass and land saving became less substantial for $SM > 1$, at $SM = 1$ the hybrid plant saved 1880 tonnes and 145 hectares per annum. Evaluating the result for the two case studies, a solar multiple of 1.5 for both plants was found to give a suitable trade-off between increased costs and environmental benefits. The levelised energy costs and payback periods were only slightly increased for the ELFR plant (0.3 ¢/kWh and 1.4 years), even though the ELFR was considerably more expensive than the LFR. This was due to the ELFR improving the solar field's energy and exergetic efficiencies by 8% and 7%, which resulted in more biomass (100 t/a) and land (9 ha/a) being saved, thus reducing O&M costs. Both case studies were simulated using a low land cost estimate for India (720 INR/m²). For a high land cost (10,000 INR/m²) the LFR and ELFR plants with a solar multiple of 1.5 would have resulted in a levelised energy cost of 43.1 ¢/kWh and 38.8 ¢/kWh respectively. Therefore, the ELFR plant would have reduced levelised energy costs by 10%. While it is unlikely that a large power generating plant would be built in a location with such high land costs, the potential of the ELFR is evident; particularly as designing for mass manufacture could significantly reduce the solar field's capital costs. With regards to levelised energy cost, a 4% decrease in the cost of the ELFR solar field or a 15% increase in land cost would have resulted in the Gujarat ELFR plant (case 2) being cost competitive with the Gujarat LFR plant (case 1),. In the case of the Gujarat hybrid LFR-biomass power plant, it was found that a Linear Fresnel Reflector of 14,000 m² aperture combined with a 3 tonne biomass boiler, <https://assignbuster.com/a-hybrid-solar-biomass-power-plant-environmental-sciences-essay/>

would generate 815 MWh per annum of electricity for nearby villages and 12,450 tonnes of ice per annum for local fisheries and food industries. However, at the expense of a 0.3 ¢/kWh increase in levelised energy costs, the ELFR would increase savings of biomass (100 t/a) and land (9 ha/a). Alternative applications for a hybrid solar-biomass plant were also modelled (Nixon et al., 2012). This found a tri-generation application to be more feasible than an electricity or process heat only plant. In comparison to biomass only operation, hybrid plants were found to soon become cost competitive due to the current rapidly increasing price of feedstock fuels.

4. Discussion

The outputs and contributions arising from the reviewed studies (Nixon and Davies, 2012; Nixon et al., 2010, 2012, 2013) in this paper are now discussed. The implications to the fields of renewable and solar thermal energy are also highlighted and remarks are made on the recommendations for further work. In response to the first objective, a literature review was used to gather quantitative data for the technical, financial and environmental considerations for solar thermal collector technologies in India and elsewhere. The Analytical Hierarchy Process was identified as a suitable multi-criteria decision-making methodology for solar thermal technology selection, and the preferred technologies for Gujarat, India, were identified as the linear Fresnel lens and reflector. While the AHP suffers from several known drawbacks – subjectivity never reduced to zero, no indication of poor judgements and result dependence on inclusion of irrelevant alternatives – it provided a strong and proven approach to decision-making, and should be used in the future for technology selection in the field of renewable energy.

To meet the second objective, a new and improved method in comparison to the conventional technique reported in the literature for specifying the mirror spacing arrangement in an LFR system was established, leading to a recommended optimum mirror spacing arrangement specified for the onset of shadowing at a solar profile angle 45° . A key contribution from the reported studies was the development of a novel solar collector termed the 'Elevation Linear Fresnel Reflector', improving an LFR's annual optical efficiency and land usage. In comparison to the conventional LFR, the ELFR increases capital costs (16–28%), however improves performance (9–25% increase in optical efficiency), reduces auxiliary fuel/storage demand (13–23% increase in operational hours) and land usage (17%), and has the potential to decrease a power plants levelised energy costs (up to 10%). Further work is desirable to reduce the ELFR's drawbacks of increased cost and complexity. There is scope to significantly reduce costs through the use of low cost mechanisms to achieve element elevation. However, the effect of elevation accuracies on the ELFR's optical performance needs to be characterised in order to determine the suitability of such mechanisms. Further cost reductions will also be achieved for an ELFR redesigned for mass manufacture. Therefore, the ELFR is thought to have considerable potential for solar thermal applications in India and elsewhere. In response to the third and final objective, models of hybrid LFR- and ELFR-biomass power plants were simulated to evaluate concept feasibility. The key technical, financial and environmental considerations for specifying the solar multiple of hybrid solar-biomass power plants were characterised as the energy efficiencies, exergetic efficiencies, cost per exergy losses, levelised cost of electricity, levelised energy cost, payback period on total capital cost, <https://assignbuster.com/a-hybrid-solar-biomass-power-plant-environmental-sciences-essay/>

payback period on cost of solar field, mass of biomass saved and resulting land saved. As a result, a solar multiple of 1.5 for the hybrid plants (an aperture area of 14,000 m²) was recommended. Simulating alternative applications of hybrid plants found an off-grid tri-generation plant to be the most feasible application for a hybrid solar-biomass power plant in India. However, hybrid solar-biomass power plants would benefit from additional research covering the solar field and other components. Hybrid plants could be analysed for a range of alternative CSP technologies, e.g. parabolic trough and heliostat field collector. Bespoke components for the heat cycle of small-scale hybrid applications should be researched to improve the low energy and exergetic efficiencies. The control system for a case specific hybrid plant will also need to be optimised. The entire hybrid plant heat cycle has also not been considered - piping layout, pump sizing, structure, etc. - and will need to be specified. Additional LFR prototypes will also need developing and finalising in India. This may include an LFR with curved mirror elements or an ELFR system to gather cost data. The studies performed for the CSP technology and hybrid plant have been primarily theoretical. The next stage for the hybrid plant project in Gujarat will be the construction of the plant using the design recommendations made in this paper. The technical aspects of the system will then need to be assessed during real operational conditions. Further recommendations are to perform site location measurements for the direct irradiance to validate the TMY model, as the effects of dust and haze in India can have major influence on the site specific insolation. The following phase for the plant will be the integration of a rice mill for concept demonstration. The commercial

feasibility of the plant will then be addressed for the deployment of additional installations.

5. Conclusion

It is considered that the solar thermal field for a hybrid solar-biomass power plant was thoroughly investigated using the structured methodology comprising engineering and management studies (see Figure 2). The decision for which solar thermal technology to pursue was made using the analytical hierarchy process. As a result of the AHP and other practical constraints, the linear Fresnel reflector was chosen. A techno-economic optimisation method for the LFR was outlined which improved performance and minimised costs. Using Quality Function Deployment and a Pugh selection matrix a novel Elevation Linear Fresnel Reflector concept was also evaluated. Combining the studies, alternative case study applications for a hybrid plant operating with an LFR type solar thermal field were analysed. The feasibility of hybrid solar-biomass applications will be case specific. However a general conclusion was that tri-generation systems have the greatest potential (considering energy and exergetic efficiencies, cost per exergy losses, levelised costs, payback periods and biomass and land saved) and should be the focus for policymakers, investors and plant developers in India. The reported research using engineering and decision science methods enabled the design details for the Gujarat plant's solar collector and solar thermal field to be specified. The preliminary research performed on the hybrid LFR-biomass power plants in India highlights the feasibility of applications for tri-generation as well as electricity generation and industrial process heat. The reported methodology will contribute towards promoting

combined engineering and management methodologies in R&D, and enhancing the candidacy of solar thermal applications worldwide.

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