

Design of a novel solar thermal collector using a multi-criteria decision-making methodology



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ABSTRACT

Three novel solar thermal collector concepts derived from the Linear Fresnel Reflector (LFR) are developed and evaluated through a multi-criteria decision-making methodology, comprising the following techniques: Quality Function Deployment (QFD), the Analytical Hierarchy Process (AHP) and the Pugh selection matrix. Criteria are specified by technical and customer requirements gathered from Gujarat, India. The concepts are compared to a standard LFR for reference, and as a result, a novel 'Elevation Linear Fresnel Reflector' (ELFR) concept using elevating mirrors is selected. A detailed version of this concept is proposed and compared against two standard LFR configurations, one using constant and the other using variable horizontal mirror spacing. Annual performance is analysed for a typical meteorological year. Financial assessment is made through the construction of a prototype. The novel LFR has an annual optical efficiency of 49% and increases exergy by 13–23%. Operational hours above a target temperature of 300 °C are increased by 9–24%. A 17% reduction in land usage is also achievable. However, the ELFR suffers from additional complexity and a 16–28% increase in capital cost. It is concluded that this novel design is particularly promising for industrial applications and locations with restricted land availability or high land costs. The decision analysis methodology adopted is considered to have a wider potential for applications in the fields of renewable energy and sustainable design.

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1. Introduction

Since initial attempts to convert solar energy for the purpose of steam generation in the mid 19th century (Kalogirou, 2004), only comparatively recently has there been a renewed interest in concentrating solar power (CSP) technologies. A CSP technology is formed from a concentrator and receiver assembly (Duffie and Beckman, 2006). The concentrator usually comprises mirrors to focus solar radiation onto a receiver. The receiver consists of an absorbing target to transfer concentrated energy, typically, to a heat transfer fluid. A range of different solar collectors with varying concentrator and receiver configurations is available on the market today; however, their designs have remained relatively unchanged since their conception.

The solar thermal collector which forms the focus of this paper is the Linear Fresnel Reflector (LFR), also known as the linear Fresnel collector (LFC). The LFR is considered to be particularly promising among CSP technologies as it benefits from a relatively

simple and inexpensive design. In comparison to the more commonly implemented parabolic trough collector (PTC), which uses large parabolically shaped reflectors and a moving receiver, the LFR employs long, thin, low profile mirror elements, spaced horizontally and located close to the ground at vary distances from a central tower, thus minimising structural requirements and wind loads. Located at the top of the receiver tower is a fixed absorber, therefore removing the need for flexible high pressure pipe lines (Fig. 1). Yet, as the LFR has less energy capture than the PTC and other CSP technologies, the need for improvements is still considered to be significant, particularly in raising the annual optical efficiency (Morin et al.).

The LFR principle was first developed by Baum et al., 1957, and later applied by Giorgio Francia in 1961, who designed both linear and two-axis tracking Fresnel reflectors (Baum et al., 1957; Francia, 1968; Kalogirou, 2004). In 1979 a large scale project was initiated by the U. S Department of Energy for a 10 MWe and 100 MWe power plant during the oil crisis, but these never came to fruition due to a lack of funding (Kalogirou and Knowel, 2009). In 1991 the Israeli Paz company constructed a LFR at the Ben-Gurion Solar Electricity Technologies Test Centre; however, due to construction difficulties resulting optical efficiencies were very low (Feuermann,

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Nomenclature

AHP	Analytical hierarchy process
ELFR	Elevation Linear Fresnel Reflector
HoQ	House of quality
H-constant	Horizontal-constant mirror spacing arrangement
H-variable	Horizontal-variable mirror spacing arrangement
IAM	Incident angle modifier
eb_n	Elevation required to remove blocking of an nth element (m)
es_n	Elevation required to remove shadowing of an nth element (m)
$E_{x,out}$	Exergy per collector aperture (maximum available power output) (W/m ²)
f_m	Final overall weighting (–)
g_m	Customer requirement importance (–)
h	Receiver height (m)
Q	Net heat transfer to receiver's absorbing target (W)
Q_{in}^*	Heat transferred in (W)
Q_{loss}	Heat loss (W)
Q_n	Distance of an nth mirror element from receiver (m)

r_{mn}	Technical and customer requirement relationship score (–)
S_n	Shift or gap between mirror elements (m)
T_a	Ambient temperature (K)
t_n	Technical priority (–)
T_r	Surface temperature of receiver's absorbing target (K)
$T_{r,max}$	Stagnation temperature (maximum temperature of receiver) (K)
u_m	Improvement factor (–)
U_L	Heat loss coefficient (W/m ² K)
W	Width of mirror elements (m)

Greek Symbols

$\eta_o(0 = \theta)$	Optical efficiency at normal incidence
η_{shadow}	Shadow efficiency
$\eta_{Blocking}$	Blocking efficiency
θ_l	Angle in the longitudinal plane
θ_n	Slope angle of an nth mirror element
θ_p	Profile angle of the sun
θ_t	Angle in the transversal plane

1993). A new variant of the LFR termed the compact linear Fresnel reflector (CLFR) was initially proposed in 1993 at the University of Sydney. It used interleaving mirrors to focus sunlight onto multiple receiver towers (Mills, 2003; Mills and Morrison, 2000). In 2001 a Belgian company, Solarmundo, installed a 2500 m² LFR prototype in Liege (Facão and Oliveira, 2011). Solarmundo later merged with the Solar Power Group, Germany, who constructed Fresdemo, a large pilot LFR system at the Plataforma Solar de Almería (P.S.A) in Spain, which was tested until 2008 (Bernhard et al., 2008a, 2008b; P.S.A, 2007). Since 2005 several LFRs have been constructed for industrial process heat applications and solar cooling in various locations across the USA and Europe, including the towns of Freiburg, Bergamo, Grombalia, and Sevilla (SolarPACES, 2008). Founded in 2006, Novatec Solar has recently development the world's first commercial LFR power plant, Puerto Errado 1 (PE 1), a 1.4 MW power plant that commenced selling power to the Spanish grid in March 2009. Puerto Errado 2, a 30 MW power plant has also begun construction in Murcia, Spain (Novatec, 2012). An extension of the CLFR design, termed 'étendue-matched', was proposed in 2010 (Chaves and Collares-Pereira, 2010). Also in 2010 Industrial Solar, previously Mirroxx, built a 1408 m² aperture area LFR for cooling of a 500 seat showase stadium for Qatar's 2020 FIFA World Cup bid (Zahler et al., 2011). In 2011 Novatec Solar and Avera claimed that superheated steam at 450 °C through direct steam generation had been achieved in their LFR systems (Conlon, 2011; Mertins et al., 2011).

A major difficulty with the LFR is shading and blocking from adjacent mirror elements which reduces annual optical efficiency. Increasing the spacing between mirrors or height of the receiver tower helps to reduce these effects, but can increase land usage and

costs. Optimisation of the LFR mirror spacing arrangement to maximise power output whilst minimising capital costs has been analysed in a cost-exergy study (Nixon and Davies, 2011). Optimisations of the LFR performance through varying the mirror width, shape, spacing, and number of mirror elements have also been reported (Barale et al., 2010; Chaves and Collares-Pereira, 2010; Häberle, 2004; Häberle et al., 2002; Morin et al., 2008; Singh et al., 1999, 2010b; Sootha and Negi, 1994; Velázquez et al., 2010). This paper differs from those earlier studies in that novel LFR concepts, which do not necessarily conform to the standard LFR design, are developed and compared.

To arrive at these novel concepts, structured design methods are used, in particular Quality Function Deployment (QFD). QFD originated in the late 1960s and early 1970s in Japan and since then has grown in popularity for use in a number of industries including automotive, software development, steel and electronics (Chan and Wu, 2002). QFD is a method that enables user demands to be transformed into design quality, priorities and targets (Akao, 1990). Researchers have suggested the use of QFD to ensure environmental awareness in product design (Masui et al., 2003) and for market strategy decision making for new housing developments (Dikmen et al., 2005). More recently QFD has been applied to the design of building integrated photovoltaic systems (Paul et al., 2008). So far, however, there have been very few (if any) references to the use of QFD in the field of solar thermal energy.

The primary and most significant tool in QFD is the 'House of Quality' (HoQ), which translates customer requirements into engineering characteristics i.e. technical requirements. A step by step illustrative application and example of the HoQ is given by (Chan and Wu, 2005). These requirements are commonly obtained through interviews, surveys and Multi-Criteria Decision-Making methods (MCDM). Approaches integrating QFD with decision-making methods such as the Analytical Hierarchy Process (AHP), goal programming and the Analytic Network Process (ANP) have been demonstrated in areas such as product planning (Karsak et al., 2003) and strategic marketing (Min Hua Lu et al., 1994). The AHP is a particularly popular MCDM method (Pohekar and Ramachandran, 2004). It breaks complex decision problems down into manageable sub-problems and provides a structured approach to analysing quantitative and qualitative data in pair-

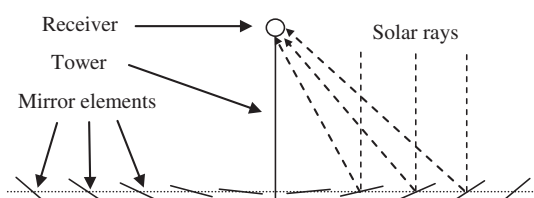


Fig. 1. Schematic of a Linear Fresnel Reflector.

wise comparison matrices. A number of publications combining AHP and QFD for product design and selection are reviewed by Ho (2008). Other decision methodologies have also been integrated with QFD to further enhance concept selection. The Pugh matrix is a systematic process for the quick selection of a 'best' concept, and is commonly used in engineering decision making to score new design concepts against a baseline design. Individual design criteria are simply rated as better or worse for each new concept; the design with the highest score is then considered the best to pursue. QFD provides an objective approach to assigning an importance to the selection criteria. A joint US Air Force/NASA program to produce a heavy lift launch vehicle used the Pugh concept selection matrix with QFD for the selection of a new fuel turbo pump, comparing two different designs with a baseline concept (Butler, 1993).

In the field of sustainable energy and manufacturing, several authors have used MCDM tools for system selection and cleaner production: Lozano-Minguez et al. (2011) used a MCDM technique to assess alternative support structures for offshore wind turbine installations; Cavallaro (2009) demonstrated an MCDM method to assess and compare alternative CSP systems; Kosoric et al. (2011) and Cavallaro (2010) have used MCDM methods for design, development and technology selection for Photovoltaics (PV); Ghadimi et al. (2012) proposed a fuzzy AHP method for product sustainability assessment for the automotive industry, and Myllyviita et al. (2012) combined MCDM with Life Cycle Assessment (LCA) to evaluate the environmental impact of biomass production. Methods such as QFD, AHP and the Pugh matrix are well documented in the literature and are therefore used here without further detailed background explanations (Akao, 1990; Pugh, 1991; Saaty, 2008).

The aim of this paper is to develop a novel LFR and thus improve on the standard LFR design in response to customer (and not purely technical) requirements. For the purpose of demonstrating the research methodology adopted, the region of Gujarat, India, has been chosen as a case study given the region's energy poverty and abundance of solar energy which is vastly underutilised. The objectives to accomplish this are as follows:

1. Using a multi-criteria decision-making methodology (QFD, AHP and Pugh), develop and select a novel LFR concept based on requirements (i.e. criteria) arising in Gujarat, India. Analyse the technical performance of a detailed design of the selected concept and an equivalent standard LFR design for comparison.
2. Construct a prototype of the novel LFR design to establish monetary values for comparison to standard design.
3. Evaluate the benefits and drawbacks of the novel design compared to the standard design, with reference to original customer and technical requirements.
4. Evaluate the effectiveness of the decision-making method in terms of incorporating customer and technical requirements, thus improving total quality.

The following section outlines a methodology that has been developed to achieve these objectives. Section 3 describes the creation of a house of quality matrix. In section 4, several novel LFR concepts are proposed and ranked in order of preference. The most preferred concept is finalised and analysed in detail in Sections 5 and 6. The paper concludes by discussing the developed methodology and implications and benefits of the new LFR design.

2. Methodology

The methodology used to reach these objectives will now be outlined.

2.1. Construction of the House of Quality

As in all QFD approaches, the customer requirements (WHATs i.e. what the customer wants) are collected for use in the HoQ. In this paper results from an AHP study, to identify the best CSP technology for Gujarat, India, are used to generate WHATs and their importance. Technical requirements (HOWs) for how the WHATs will be satisfied are also determined. The main outputs from the completed HoQ are technical priorities (weightings) for each HOW for the design of a novel LFR. Technical targets, limits and difficulties are also specified to develop product specifications.

2.2. Concept development and selection

Three concepts for a novel LFR are developed. A Pugh matrix is completed by scoring the technical requirements as better or worse in each concept in comparison to a reference baseline LFR design. To arrive at a final overall ranking, the HoQ technical priorities are assigned to the Pugh matrix and the LFR design with the highest total score is selected.

2.3. Finalized design of selected concept

A detailed design of the selected novel LFR concept is developed, while targets and limits are maintained based on those specified in the HoQ.

2.4. Detailed analysis of selected LFR with standard design

The novel design is analysed through the use of ray-tracing to enable annual performance to be predicted over a typical meteorological year (TMY) for the region of Gujarat, India. Performance results include exergy per total mirror area, operational hours above a target operating temperature, net heat transfer to receiver and annual optical efficiency. The annual performances of two standard LFRs are also analysed for comparison. Financial results are determined through the construction of a prototype; and upper and lower land costs are researched for Gujarat. Capital costs and achievable cost per exergy among the final designs are evaluated and compared.

3. Construction of the House of Quality

The customer requirements were extracted from importance weightings attributed by a panel of solar energy specialists working at the Solar Energy Centre in Delhi, India. This panel was convened for an earlier AHP study, which was reported by the authors in Ref. (Nixon et al., 2010). The panel weighted a series of technical, financial and environmental criteria applicable to the selection of the preferred CSP technology for use in India, and a pair-wise comparison matrix was completed to arrive at individual relative weightings (Fig. 2). Criteria from the aforementioned AHP study that relate to WHAT the customers want were identified as ease of operation and high heat quality, which relate directly to use of standard parts and a high concentration ratio, reliability, land usage, cost of operations and capital cost. The relative weightings were used to assign a low (1), medium (3), and high (9) importance, g_m , to the WHATs, W_m , (Table 1). The technical requirements provided from the AHP results were expanded to include additional HOWs, H_n , deemed necessary for the design of a novel solar collector for India. An additional input to the HoQ was included to reflect an improvement factor, u_m , given by the ratio of the 'future product' rating, a_m , to 'current product' rating, x_m . A standard LFR was scored against the customer requirements, and compared to a target score for a novel design. A final overall weighting, f_m , was

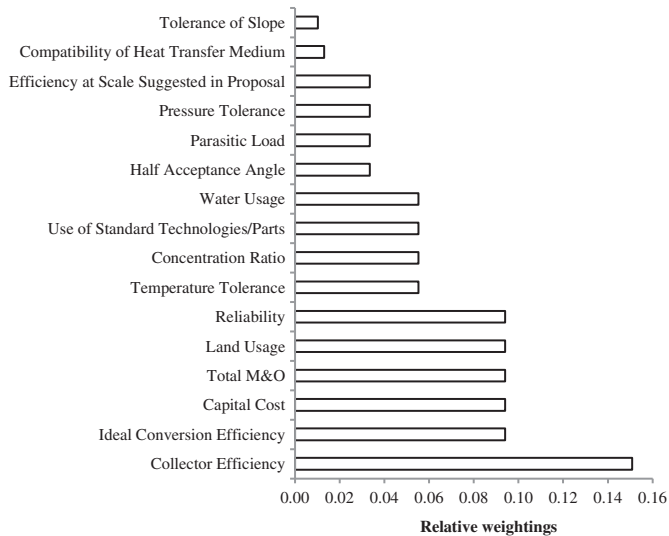


Fig. 2. Weightings attributed to by an expert panel for technical, financial and environmental criteria in the selection of a solar thermal collector for India, using the Analytical Hierarchy Process (Nixon et al., 2010).

formed from the product of the customer's importance score and the design improvement factor.

$$f_m = g_m \cdot u_m \quad (1)$$

To complete the HoQ relationship matrix, each HOW was scored against each WHAT on whether there was a weak (1), medium (3), or strong (9) relationship. The correlation matrix was omitted for simplicity. The importance, t_n , of each technical requirement was established by multiplication of each value in the relationship matrix, r_{mn} , by the respective overall weighting and totalling the scores for each technical requirement (Chan and Wu, 2005). A relative technical priority was established through normalisation. The completed HoQ included a target or limit and a technical difficulty for each HOW (see Fig. 3).

$$t_n = \sum_{m=1}^M f_m \cdot r_{mn}, \quad n = 1, 2, \dots, N \quad (2)$$

The HoQ identified the most important customer requirement to be land usage with an overall weighting of 14, followed by the capital cost with a weighting of 6.8. Ease of operation was found to be the least important customer requirement with a score of 1.8. The technical priorities revealed the cost per exergy to be the most important technical requirement with an 11% priority. With a priority of 7% the following technical requirements were ranked in second: reflectivity of the mirror elements, accurate tracking, half acceptance angle and concentration ratio.

Table 1

Customer requirements and their importance for a solar collector in India, established from an AHP study.

Customer requirements	Customer importance
Ease of operation/set-up	3
High quality of heat	3
Reliability	9
Land usage	9
Cost of O&M	9
Capital cost	9

4. Concept development and selection

Three LFR concepts, Circular, Parabolic and Elevation, were consequently developed taking into account the customer and technical requirements and their weightings. Each LFR concept comprised a concentrator, formed from mirror elements, focussing on a fixed insulated target (the design traits typifying an LFR). Schematics of the three concepts and a standard LFR design (Horizontal) used as a baseline are shown in Fig. 4a–d, which distinguishes the tracking method and element location in each case. A Pugh selection matrix was used to compare the novel LFR concepts in comparison to Horizontal. In the matrix concepts were scored against each technical requirement as better '1', even '0', or worse '−1'. Each score was then multiplied by the corresponding technical priority and totalled to provide a final weighted ranking. Among the alternatives the 'Elevation' concept, henceforth referred to concisely as the Elevation Linear Fresnel Reflector (ELFR), received the highest weighted ranking (see Table 2).

5. Finalised design of selected concept

A final ELFR design using 8 mirror elements, each 250 mm wide and spaced 260 mm apart (10 mm gap), was chosen to satisfy the specified targets and limits. This formed a single LFR unit 4 m in length. A secondary compound parabolic concentrator (CPC) at the receiver aperture was also chosen to maintain the capture of rays from the collector extremity for changing element focal distances. Through the use of a CPC the width of the receiver's absorbing target was reduced, thus overcoming the disadvantage of using wide flat mirror elements. The target absorber was a 63.5 mm diameter pipe located at a height of 5 m, with a truncated CPC so the receiver was not oversized. This provided the target concentration ratio of 30 as specified in the HoQ. To simplify the construction of a prototype the receiver was positioned at the maximum practical height of 2.5 m, resulting in a receiver absorbing target width of 152.4 mm; thus, three 63.5 mm pipes were selected (see Fig. 5). The detailed design method for a CPC can be found in the literature and is therefore not presented here (Duffie and Beckman, 2006; Welford and Winston, 1989).

6. Detailed analysis of selected LFR against standard design

Technical and financial criteria of the finalised ELFR were evaluated with reference to two equivalent Horizontal LFR designs with different spacing arrangements; 'H-constant' having mirror elements with a horizontal-constant spacing of 260 mm (the same spacing as the ELFR design), and 'H-variable' having horizontal-variable spacing such that the onset of shadowing among adjacent elements occurs at a solar transversal angle of 45° (see Fig. 6). Note that the wider mirror spacing of H-variable requires a redesigned CPC. The technical performance of each design was calculated from the maximum available power output (i.e. exergy) at the receiver's absorbing target surface. The financial factors considered were the land usage and the capital costs incurred from the LFR sub-components, which included the receiver, concentrator elements and frame.

6.1. Technical analysis

Achievable performance was predicted in this case for an LFR with specified location and mirror element arrangement with a north–south axis tracking orientation over a TMY for Gujarat. Since the focus of this study is on the collector design, the concept of exergy is used to provide details on the maximum available power output for a given operating absorber pipe surface temperature and ambient temperature. The exergy approach assumes an idealised

		Customer Importance (g_m)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
		Energy	Collection Efficiency		Optical Efficiency		Ideal Conversion Efficiency		Reflectivity of Concentrator Elements		Use of Standard Parts		Durable		Tolerance of External Loads		Accurate Tracking		Half Acceptance Angle (Secondary Concentrator)		Concentration Ratio		Efficient Use of Land		Average Daily Shadow Efficiency		Parasitic Loads		Temperature Tolerance		Heat Transfer Characteristics		High Absorption		Compatible with Heat Transfer Fluid		Pressure Tolerance (Fixed Receiver)		Cost per Exergy		Typical LFR Design (x_m)		Target Rating (a_m)		Improvement Factor (u_m)		Overall Weighting (f_m)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
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Fig. 3. House of Quality constructed for the design of a novel LFR for India.

Carnot cycle and therefore detailed assumptions that would be required for modelling a complete plant, such as piping layout, flow rate and choice of heat transfer fluid and heat engine, are not required. While a drawback of the exergy approach is that specific applications are not considered, exergetic analyses have still been widely adopted in the solar literature (Gupta and Kaushik, 2010; Singh et al., 2000; Tyagi et al., 2007). Exergy per unit area (given in W/m² of collector's total mirror area) as an hourly average in the TMY for an LFR is calculated from:

$$E_{x,out} = Q \left(1 - \frac{T_a}{T_r} \right) \quad (3)$$

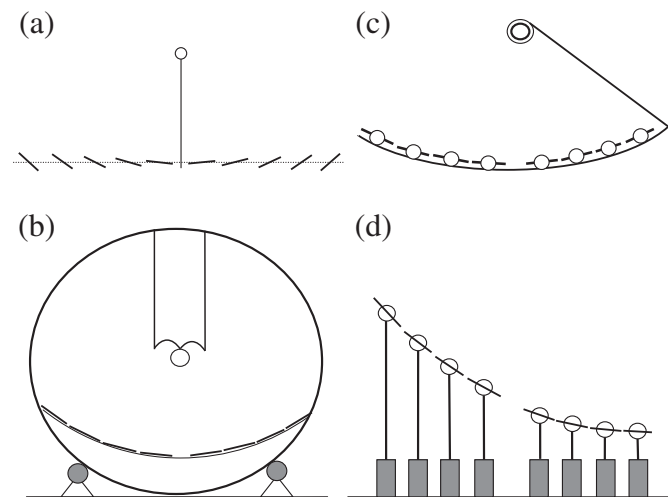


Fig. 4. a–d: Reference LFR concept (a) Horizontal – horizontal rotating elements. LFR concepts (b) Circular – elements located along parabola rotating in a circular wheel, (c) Parabolic – rotating elements placed along parabolic path and (d) Elevation – rotating and elevating elements.

where Q , the net heat transferred to the outer surface of the receiver's target, at a temperature T_r , which is given by:

$$Q = Q_{in} - Q_{loss} \quad (4)$$

where Q_{loss} is the heat loss to ambient (temperature T_a) and depends upon the receiver configuration. Thermodynamic

Table 2

Pugh concept selection matrix for a novel LFR. The concept Elevation (ELFR) obtained the highest final weighted ranking.

Technical requirements	Technical priorities	Horizontal (a)	Circular (b)	Parabolic (c)	Elevation (d)
Exergy	2%	0	1	1	1
Collection efficiency	4%	0	1	0	1
Optical efficiency	5%	0	1	0	1
Ideal conversion efficiency	3%	0	1	0	1
Durable	7%	0	0	0	0
Concentration ratio	4%	0	1	1	1
Use of standard parts	5%	0	–1	–1	–1
Parasitic loads	2%	0	0	0	0
Efficient use of land	7%	0	1	0	1
Tolerance of external loads	7%	0	–1	0	0
Reflectivity of concentrator elements	7%	0	0	0	0
Average daily shadow efficiency	6%	0	1	0	1
Accurate tracking	6%	0	1	0	1
Temperature tolerance	3%	0	0	0	0
Heat transfer characteristics	4%	0	0	0	0
Specialist coatings	5%	0	0	0	0
Compatible with heat transfer fluid	5%	0	0	0	0
Pressure tolerance (fixed receiver)	4%	0	0	0	0
Half acceptance angle (secondary concentrator)	3%	0	1	–1	0
Cost per exergy	11%	0	0	0	0
Total score		0	7	0	7
Final weighted ranking		0	0.2772	–0.0126	0.3215

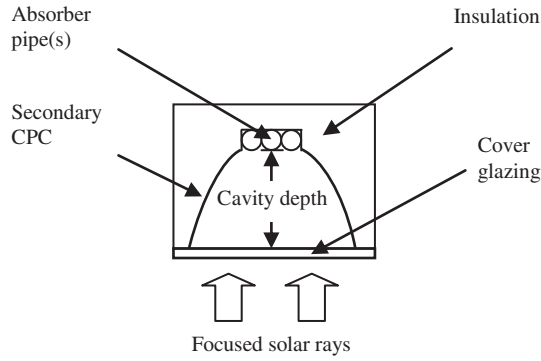


Fig. 5. Schematic of an insulated receiver configuration with secondary CPC.

calculations for two commonly employed receiver types (non-evacuated insulated pipe(s) with cover glazing, and evacuated tube) are given in the solar literature (Duffie and Beckman, 2006; Singh et al., 2010a). Heat transferred to the receiver, Q_{in}^* , is a product of the direct solar irradiance (DNI) on the collector's total mirror area, A_m , the optical efficiency at normal incidence, $\eta_0(0 = \theta)$, and the incidence angle modifier (IAM), which accounts for the optical performance for varying solar ray incidence angles. Collector end losses are not considered.

$$Q_{in}^* = \text{DNI} \cdot A_m \eta_0(0 = \theta) \cdot \text{IAM} \quad (5)$$

The optical efficiency and the IAM include factors such as the reflectance, transmittance, absorbance, intercept factor, shadowing, blocking, effective mirror aperture area, and incidence cosines for each mirror element. The individual mirror element elevation required throughout operation to remove shadowing, es_n , can be approximated from the corresponding width, W , slope angle, θ_n , and shift, S_n (the horizontal gap between adjacent mirror elements).

$$es_n = \frac{W}{2} (\sin\theta_n + \sin\theta_{n+1}) - S_n \tan\theta_p \quad (6)$$

Where the sun's height is represented by the profile angle, θ_p , which is the angle projected onto a plane perpendicular to the mirror tracking axis, formed between an approaching sun vector and the plane containing the axes of rotation of the mirrors (see Fig. 7). Equations relating to sun-earth geometry calculations are not presented (Muneer et al., 2004; William et al., 2001). With a change in elevation an iterative process is required to calculate the

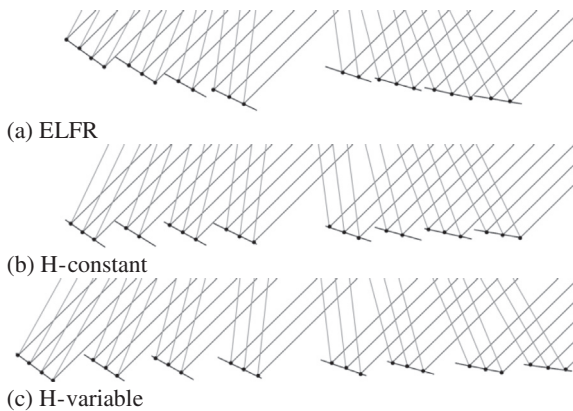


Fig. 6. Mirror spacing arrangement for a (a) ELFR, (b) H-constant and (c) H-variable design for solar rays approaching at a transversal angle of 45° .

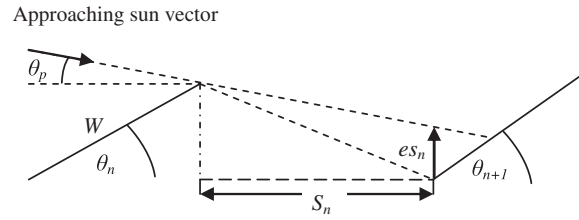


Fig. 7. Elevation required to remove shadowing from an adjacent mirror element.

correct slope angle. Depending upon the LFR geometry a narrow spacing arrangement may result in blocking of reflected rays from adjacent mirrors. The elevation to removing blocking is estimated by:

$$eb_n = \frac{W}{2} (\sin\theta_{n+1} + \sin\theta_n) - \frac{S_n h}{(Q_{n+1} + (\frac{W}{2}) \cos\theta_{n+1} + S_n)} \quad (7)$$

where h is the height of the receiver and Q_n is the horizontal distance from a mirror element to the receiver tower (see Fig. 8). The tracking arrangement from sunrise to sunset for the ELFR is shown in Fig. 9.

The LFR shows a bi-axial dependency in relation to the direct solar incidence angle (Duffie and Beckman, 2006). A bi-axial IAM(θ_t, θ_l) was therefore used in this study, which includes an angle modifier for rays in the transversal plane IAM(θ_t) (i.e. the vertical plane perpendicular to the rotation axes of the elements), and longitudinal plane IAM(θ_l) (i.e. the vertical plane parallel to the rotation axes of the elements) (McIntire, 1982). Bi-axial IAMs are typically calculated using ray-tracing (Nixon and Davies, 2011). An estimate for the total optical efficiency is based on a product of IAM(θ_t) and IAM(θ_l), determined by projecting the solar incidence angle into the transversal and longitudinal planes respectively.

An incident angle dependent optical efficiency enables hourly stagnation temperatures, $T_{r,max}$, to be calculated. The stagnation temperature is reached when heat loss to the surroundings becomes equal to incoming radiation.

$$T_{r,max} = T_a + \frac{\text{DNI} \cdot \eta_0(\theta = 0) \cdot \text{IAM} \cdot A_m}{U_L A_r} \quad (8)$$

where U_L is the heat loss coefficient and A_r is the area of the receiver. If the stagnation temperature is below that of a target operational temperature then it was assumed that the captured radiation is not utilized. Thus, the collector is not operating. The heat loss has been estimated using parallel plate correlation, which considers heat losses from the bottom of the receiver through convection and radiation, and conduction from the insulated sides (Singh et al., 2010a). The heat loss, Q_{Loss} , is therefore given by:

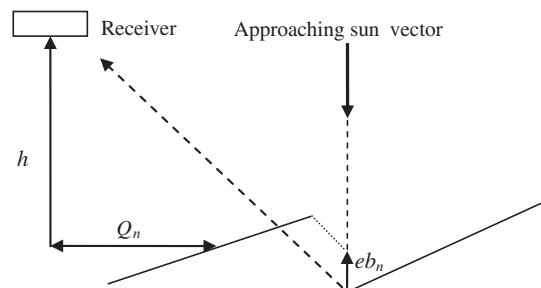


Fig. 8. Elevation required to remove blocking from an adjacent mirror element.

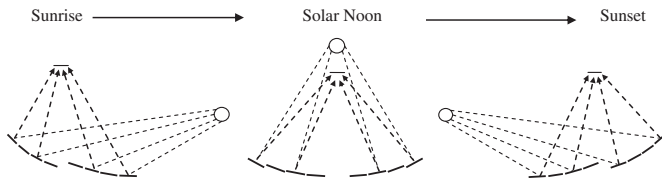


Fig. 9. Tracking arrangement of the mirrors elements from sunrise to sunset for the ELFR.

$$Q_{\text{Loss}} = A_r U_L (T_r - T_a) \quad (9)$$

6.2. Performance results

Performance characteristics of the three designs – ELFR, H-constant and H-variable – were evaluated for the Gujarat TMY. For each design the optical efficiency at normal incidence ($\theta = 0$) and the incident angle modifiers $\text{IAM}(\theta_t)$ and $\text{IAM}(\theta_l)$ were determined through ray-tracing performed in Optica, a software package developed within Mathematica®. The $\text{IAM}(\theta_t)$ and $\text{IAM}(\theta_l)$ for each design are shown in Figs. 10 and 11. The average hourly exergy (per total mirror area) and the average daily number of operational hours (for a target operating temperature of 300 °C) for each month are shown in Figs. 12 and 13 respectively. Exergy and operational hours are characteristically low during the Indian monsoon season, after reaching a peak in April–May.

The ELFR design achieved a 23% exergy increase over H-constant and a 13% increase over H-variable. A 24% and 9% increase in the operational hours was found to be achievable in comparison to H-constant and H-variable respectively. Exergy and operational hours are increased due to the ELFR's improved optical performance for low solar altitude angles. The improved optical performance results in a higher annual optical efficiency in comparison to a typical LFR. The annual optical efficiency is based on the average optical efficiency for daylight periods during a year. The average hourly exergy, total operational hours above an operating temperature of 300 °C, net heat transfer to the receiver target and annual optical efficiency are shown in Table 3.

6.3. Financial results

Through the construction of a prototype ELFR, monetary values were gathered for the collector's receiver, concentrator, frame and additional costs for the elevating elements (see Fig. 14). To provide

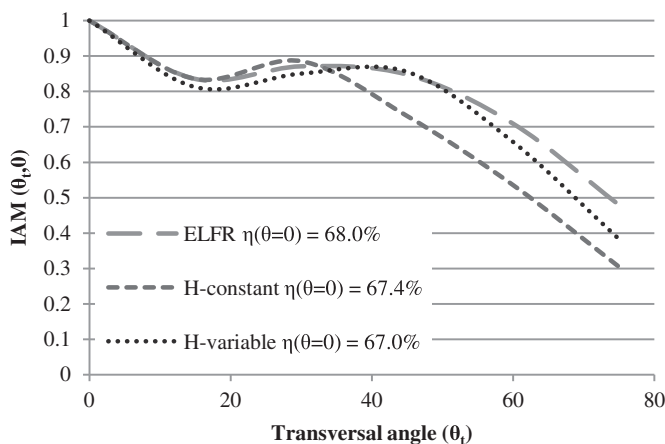


Fig. 10. IAM for changing angles in the transversal plane for ELFR, H-constant and H-variable. The optical efficiency at normal incidence is also shown for each design.

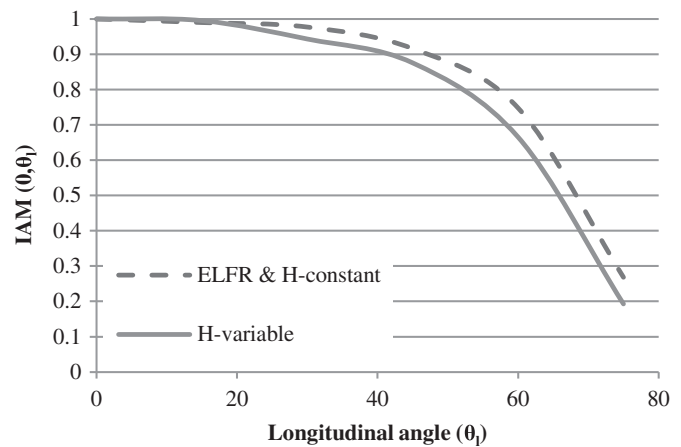


Fig. 11. IAM for changing angles in the longitudinal plane for ELFR, H-constant and H-variable.

sensitivity to the results, upper and lower land costs researched for the region of Gujarat. A final capital cost per exergy is calculated to compare the design alternatives. Units of US dollars are used, converted from Indian national rupees (INR) and pound sterling (GBP) at 2011 rates (see Table 4).

The ELFR increased the cost per exergy by potentially 2–5% and 6–13% over H-constant and H-variable respectively. The additional cost for the elevating elements, achieved through the use of linear slides and parallel pair linear actuators, formed approximately 20% of the total capital cost.

7. Discussion

It is interesting to evaluate the methodology used in this study. Assigning an importance to the customer requirements in QFD analyses is always an issue, and one that has been addressed though the use of AHP by several authors (Ho, 2008). However, while AHP provides a framework to systematically establish and prioritise different customer requirements, the further integration of a Pugh matrix enables concept design improvements to be simultaneously evaluated against customer, as well as technical, requirements and their priorities. The combination of QFD, AHP and the Pugh matrix is a relatively complex procedure. A simpler approach would be to use the Pugh matrix alone, but this would not include the formulation of technical priorities as achieved through

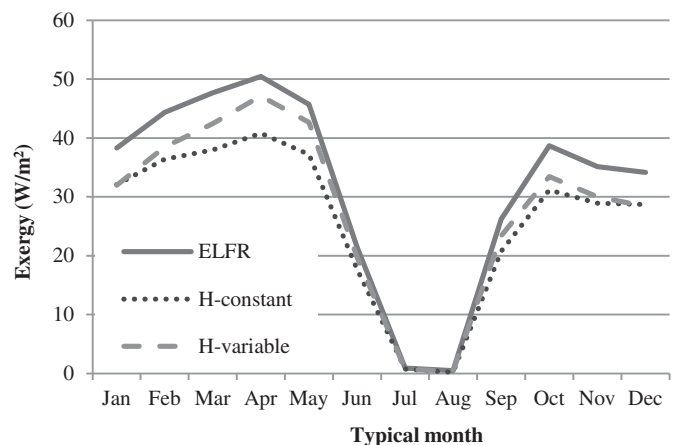


Fig. 12. Average hourly exergy for each month in a TMY for Gujarat.

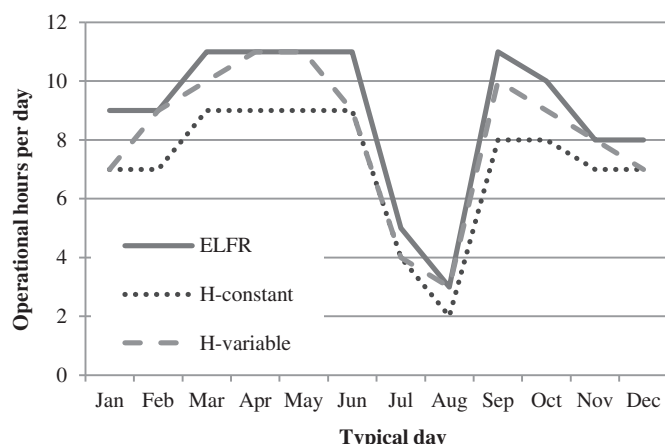


Fig. 13. Average number of operational hours at a constant operating temperature of 300 °C for a typical day in each month for Gujarat.

the complementary use of QFD and AHP. As a result, the more complex approach enabled the concepts to be differentiated. It highlighted the advantages of the ELFR concept with a 15% preference over the Circular concept.

A general criticism of systematic approaches to design decision and selection making, like QFD and AHP, is that the outcome can be rather dependent on the criteria fed into the process (i.e. the customer and technical requirements) (Hazelrigg, 2003; Olewnik and Lewis, 2005). According to this initial choice a different concept may emerge as 'the best'. To address this concern, we have taken the investigation a step further through a detailed technical and financial analysis, with comparisons made against two standard LFR designs (H-constant and H-variable).

The novel ELFR shows performance advantages. For a constant operating temperature of 300 °C, the ELFR gives a 13% increase in exergy, 274 additional operational hours per annum and a 17% reduction in land usage. This is compared to H-variable which refers to a horizontal mirror spacing arrangement specified for the onset of shadowing at a solar transversal angle of 45°. An even more significant increase in exergy of 23% is expected over a commonly employed narrow constant horizontal mirror spacing arrangement, H-constant. As regards annual optical efficiency, a value of 49% is predicted for the ELFR, compared to 45% and 39% for H-variable and H-constant respectively. It is interesting to note that these figures are comparable to an annual optical efficiency of 43% reported by (Morin et al., 2012) for the Fresdemo LFR.

There are, however, some potential financial drawbacks to the ELFR. The cost per exergy is increased by 2–5% and 6–13% in comparison to H-constant and H-variable respectively, due to the additional expense of the elevating elements. However, costs for the prototype system are not a true reflection of the manufacturing costs to be expected with mass production. A 60% reduction in component costs would result in the ELFR having a lower cost per exergy, for a high land cost scenario, in comparison to H-constant and H-variable.



Fig. 14. The ELFR prototype, constructed on the roof at Aston University, UK.

The preferred choice of design will depend on the priorities at hand. The ELFR will be interesting for industrial process heat applications or roof installations where land is less available or more expensive. The efficient land usage will be of further benefit when considering additional factors such as ground preparation, piping requirements and pipe thermal losses. The higher obtainable temperatures for longer periods of the day will also be advantageous in solar thermal power plants for electricity generation, increasing full load hours and storage capabilities. However, with the ELFR system increasing capital cost and complexity, significant improvements will be required make a commercial scale ELFR electricity power generating plant feasible.

Additional work is desirable to reduce the ELFR's drawbacks and to improve the cost effectiveness of the technology. For the prototype, cost and complexity was reduced through developing serial communication boards to simplify control and reduce cabling and auxiliary electrical loads. Embedded control systems would be employed for large scale installations to further minimise complexity. Custom designed low cost mechanisms to achieve element elevation will significantly reduce costs, as the prototype utilised expensive linear actuators of high power and accuracy. In addition, the ELFR frame was constructed from expensive high-tensile aluminium profiles and fastening elements to overcome problems of restricted access onto the roof and the unavailability of welding and heavy lifting equipment. A final ELFR product for installation in a solar thermal field would be designed for mass production and therefore further cost reductions will be achievable.

Table 3

Annual performance for the ELFR, H-constant and H-variable; annual exergy, operational hours, net heat transfer to receiver, and optical efficiency.

LFR designs	Exergy per total mirror area W/m ²	Operational hours per annum hrs/a	Net heat transfer per unit length kWh/m.a	Annual optical efficiency %
ELFR	32.0	3255	1192	49.0
H-constant	26.1	2616	972	39.3
H-variable	28.2	2981	1054	45.0

Table 4

Prototype component costs and cost per exergy for each design alternative (exchange rates: 0.0209 \$/INR, 1.5729 \$/GBP).

Design		ELFR	H-constant	H-variable
Exergy per total mirror area	W/m ²	32.0	26.1	28.2
Land usage per collector unit	m ²	9.6	9.6	11.6
Lower total land cost	\$	145	145	175
Upper total land cost	\$	2009	2009	2428
Frame	\$	6040	6040	6112
Drives for elevation	\$	3429	0	0
Concentrator elements	\$	3932	3932	3932
Receiver	\$	1887	1887	1887
Total lower cost	\$	15,433	12,004	12,107
Total upper cost	\$	17,298	13,869	14,360
Lower cost per exergy	\$/W	60.3	57.6	53.6
Upper cost per exergy	\$/W	67.6	66.5	63.6

Optimisation of the mirror geometry and number will also improve the overall cost effectiveness of the ELFR concept.

In future studies, the methodology could be improved by generation of more concepts to be combined and refined in the Pugh matrix. The Elevation design could also be applied to LFR systems employing wider mirrors with slight curvature, to the compact linear Fresnel reflector (CLFR) and to the étendue-matched CLFR (Chaves and Collares-Pereira, 2010; Mills and Morrison, 2000).

8. Conclusion

A novel Elevation LFR has been selected and analysed with the aid of a multi-criteria decision-making methodology. Continuous reference to a standard LFR design has been made throughout the design and decision processes. The performances of the novel design and two standard LFR designs have been analysed through a technical study. Through the construction of a prototype, a financial assessment of the novel design has been completed. With reference to the original aims and objectives, the following conclusions are drawn:

1. The Elevation LFR design increases the annual exergy, optical efficiency and operational hours by 13–23%, 9–25% and 9–24% respectively.
2. Capital costs increase by 16–28% for the novel LFR over the standard LFR design. The cost per exergy increases by 2–13% depending upon land costs. The Elevation LFR also reduces land usage by as much as 17%.
3. The novel LFR improves land usage which was the highest overall weighted customer requirement (14). However, capital costs (weighting of 6.8) increase and reliability (6) and ease of operation (1.8) decrease due to the larger number of drives and mechanisms. The ELFR also improves the quality of heat (6). Operations and maintenance costs (9) are likely to remain similar to the conventional LFR with the majority of costs coming from operating system pumps and fans. See Figure 4.1 for the development of the customer requirement weightings.

It was further concluded that the novel LFR is particularly suited for applications with low land availability and high land costs e.g. industrial locations and rooftops. For rural regions of India that have a greater abundance of land a standard LFR is preferred.

The methodology integrating AHP, QFD and Pugh has helped to generate and select a novel design of a solar thermal collector and will have a wider potential in the fields of renewable energy and sustainable design. Given the growing size and complexity of energy projects, these methodologies or variants may have a role to play in co-ordinating decision activities among large teams.

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