Which is the best solar thermal collection technology for electricity generation in north-west India? Evaluation of options using the Analytical Hierarchy Process.

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Abstract

This study of concentrating solar thermal power generation sets out to evaluate the main existing collection technologies using the framework of the Analytical Hierarchy Process (AHP). It encompasses parabolic troughs, heliostat fields, linear Fresnel reflectors, parabolic dishes, compound parabolic concentrators and linear Fresnel lenses. These technologies are compared based on technical, economic and environmental criteria. Within these three categories, numerous sub-criteria are identified; similarly sub-alternatives are considered for each technology. A literature review, thermodynamic calculations and an expert workshop have been used to arrive at quantitative and qualitative assessments. The methodology is applied principally to a case study in Gujarat in north-west India, though case studies based on the Sahara Desert, Southern Spain and California are included for comparison. A sensitivity analysis is carried out for Gujarat. The study concludes that the linear Fresnel lens with a secondary compound parabolic collector, or the parabolic dish reflector, are the preferred technologies for north-west India.

1. Introduction

Since independence in 1947, India has increased its electrical generation capacity from 1.4 to 148 GW, but has largely neglected its solar resource [1]. The current grid connected fuel mix is 63% fossil-thermal, 3% nuclear, 25% hydroelectric and 9% from other renewable resources; whereas grid connected solar generation capacity is a mere 2 MW [2]. Recently, however, the Indian Government has announced a new policy direction through its National Action Plan on Climate Change, one of whose eight national missions, namely the National Solar Mission, proposes substantial investment in R&D and infrastructure to increase the share of solar energy within the total energy mix [3].

India benefits from a sunny climate, in particular in its north west region, which receives some 5.5 kWh/m^2 of solar energy daily. To take advantage of this resource, one option that is currently of much interest is Concentrating Solar thermal power (CSP). This technology has been successfully implemented in California, and is being vigorously promoted for schemes to provide Europe with power from the Sahara. Detailed feasibility studies for such schemes have been prepared [4, 5]. In India, the uptake of solar thermal electricity has so far been limited to demonstrations, though solar thermal concentrators are currently used in at least two locations to provide heat for milk pasteurisation processing and cooking [6, 7].

This study has arisen in the context of a project to construct and test a solar power plant in Gujarat. During the early stages of the project, it became apparent that a factor critical to the success of the plant would be the correct selection of the solar collector technology for use in India. Elsewhere in the world the preferred choice has been the parabolic trough type, which is used in most of the large installed CSP plants in the US and Spain. Alternatives are being actively pursued, however, such as heliostat type concentrators with central tower receivers and parabolic dishes coupled to Stirling engines. As is frequently the case with energy technologies, there is a myriad of options each with its advantages and drawbacks. Moreover, the best solution for India may not be the same as for the US or Europe, as the economic and technological environment is different.

The aim of this paper is to review and evaluate the competing solar thermal collection technologies applicable to electricity generation in India with the help of a structured method. Specifically, the objective is to provide a recommendation about which technologies to pursue in the context of the current project in Gujarat and others that are expected to follow. The Analytical Hierarchy Process (AHP) has been adopted because it is a decision-making tool well suited to multifaceted problems where simple cost-benefit analysis is too simplistic. It is a process that facilitates discussion among the designers and other stakeholders. Furthermore, it generates documentation thus lending transparency to the decision making rationale. The process is based both on mathematics and psychology to provide an overall answer and differs from other decision making models by encompassing both certain and uncertain data. The essence of the process is that judgment is used to evaluate the problem as well as factual information and expert opinion. This is particularly useful in the case of evaluating solar concentrator technologies where the varying scale and prototype nature of some of these systems gives uncertainties when drawing a direct comparison between their operating characteristics [8].

Saaty, who originated AHP in the 1970s, described applications ranging from transportation planning to choosing a school for his son [9]. More recently, AHP and other multi-criteria decision making (MCDM) methods have been applied to many issues in energy planning, as reviewed by Pohekar and Ramachandran [10] along with other energy selection decisions including the assessment of oil pipeline inspections and energy resource allocation for households [11-13]. One paper from Marttunen and Hamalainen uses the AHP process to help assess the environmental impact of hydropower [14]. Bhattacharya and Dey use the AHP for power sector market selection in southern India [15]. Kaya and Kahraman use a combined Fuzzy and the AHP approach for renewable energy planning in Istanbul. The AHP is a tool that is being consistently used for the implementation and growth of technology throughout the energy sector [16, 17]. In this sector, it is typical to find a large choice of technologies, surrounded by controversial issues and variations in expert opinion. This makes AHP a particularly valuable tool that can be used to help obtain a consensus.

The essence of AHP is that it simplifies a complex decision by decomposing the problem into a hierarchy of ‘criteria’ or sub problems to be analysed individually. In this study, we have categorised the evaluation criteria as technical, economic and environmental related. The methodology is outlined as follows (see fig.1).

1. A comparative literature review of solar collector technologies has been carried out. The output is a shortlist of technology alternatives and evaluation criteria.
2. The technology alternatives were scored against the criteria, through a pair-wise comparison of factual data from the literature review. In addition, a thermodynamic analysis has been used to provide numerical values against certain criteria.
3. A workshop has been convened among solar energy experts in India, at which the technological alternatives and criteria were presented. The expert panel was invited to review the criteria and weight them for four case studies to produce a set of recommendations.

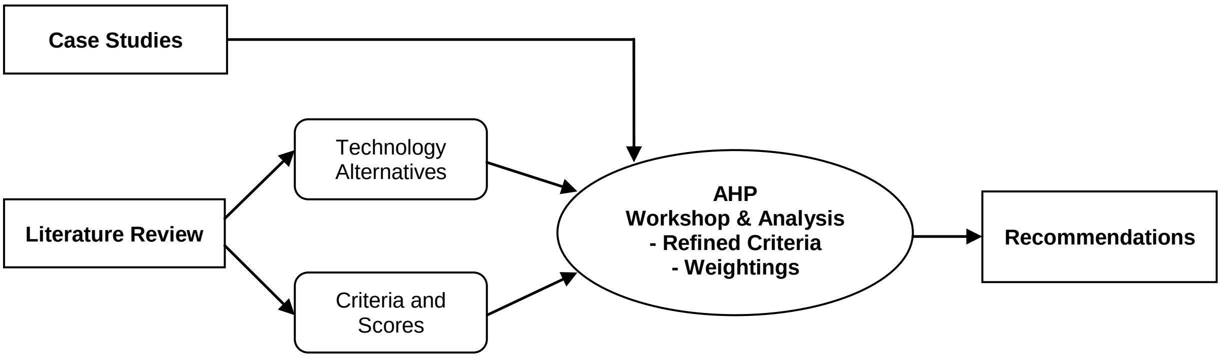


Fig.1. Flow diagram showing the methodology for technology evaluation and selection based on the AHP.

The choice of case studies encompassed the target location of Gujarat and three others: California's Mojave Desert, Southern Spain and the Sahara desert. These last three were included to broaden the frame of reference to include locations where CSP plants are already operational, or where advanced stages of planning have been carried out. The outcome is a recommendation of a solar thermal collection technology in each case.

2. Comparative literature review

The purpose of this review is to identify the main technology alternatives relating to solar collectors, to define the criteria (technical, economic and environmental), and to research factual data for use in the AHP study. Some new or little-investigated technologies are deliberately neglected due to the paucity of relevant information. For reviews of more general scope the reader is referred elsewhere [18].

2.1 Parabolic Trough Collector (PTC)

Parabolic trough collectors (PTCs) are typically made from highly reflective glass mirrors using a single-axis tracking mechanism to follow the sun's trajectory, thus focusing the solar energy onto a linear receiver at the focal axis. Typically, the receiver is an evacuated glass tube and absorbing pipe, carrying synthetic oil for the heat to be transferred to a heat exchanger, in order to power a conventional steam power plant. Such PTCs can concentrate direct sunlight to generate working temperatures up to 400ºC [19] and achieve concentration ratios in the range of 30 – 100. The world’s largest solar thermal facility is currently the nine Solar Energy Generating Systems (SEGS) built by Luz Industries in the Mojave Desert in California providing a total installed capacity of 354 MW [20].

Collector fields usually follow a north-south alignment with careful consideration given to the distance between collector rows, as this distance will determine the amount of land and piping used and therefore affect costs. It also affects fluid transport and optical shadowing losses which in turn affect the efficiencies of the system [21]. Optical efficiencies of 80% have been obtained at the SEGS, with a land usage of 3.2 m^2/MWh/year [20, 22]. The on-line parasitic load of the SEGS VI system varies monthly, but is on average around 10% of the Gross Solar Output [23]. The newer SEGS VI – VII increased the outlet temperature from the solar field from 320 – 390 ºC to raise the generated steam at the heat exchanger to a pressure of 100 bar. For the parabolic trough collector stagnation temperatures in the region of 600 ºC are typical [20]. The half-acceptance angle for a PTC is around 0.5º [18, 24]. For the standard PTC, the projected total operational and maintenance cost is approximately 0.02 $/kWhe and a total capital cost of 3972 $/kW or 424$/m^2 [20, 25].

Though synthetic oil has been used in the absorbing tubes of most PTCs to date, this transfer medium limits the operating temperature to around 400ºC. Molten salt has been suggested, but only prototype systems have been built due to the problems of the higher viscosity and high melting temperatures requiring trace heating. An alternative that has been investigated is to have water and steam being produced directly in the absorber tubes [21]. In these systems steam is generated directly in the solar field, thus avoiding the costs of heat transfer fluid and the central oil heated steam generator. The pumping requirements and thermal losses are also smaller as the field temperature can be reduced without affecting the steam temperature, and the heat transfer fluid is absent. The system is not without its technical challenges, with the risk of overheating tubes and potential flow instabilities. Sophisticated controls are required to accommodate the use of the two-phase flow of water and steam. Luz Industries, who plan to commercialize the technology, have projected that efficiencies would be improved, with capital costs reduced to around 2100 – 2300 $/kW. It has also been conceived that in direct steam generation (DSG) systems, the solar field can act as an evaporation stage, with turbine exhaust gas used for superheating and preheating in a conventional gas turbine combined-cycle power plant. The overall cycle efficiencies are again expected to increase with higher working steam temperatures achieved for the same level of heat use [20].

The Plataforma Solar de Almería (PSA) in Spain has installed a 2 MW plant to carry out a number of experimental investigations into the behaviour of steady-state and transient flow in direct steam generation parabolic troughs. The two-phase flow and stress on the receivers for different operating and process conditions are of particular interest. In direct steam generation there are three process methods, each with its benefits and disadvantages. They are the once-through, the injection, and the recirculation process [26]. In terms of process conditions, a recirculation-mode over a once-through-mode has been shown to be of greater benefit in terms of stability and stress on the absorbers [27, 28]. This represents one of the greatest problems in direct steam generation. The deformation and bending on the receivers during stratified two-phase flow due to the thermal stresses is difficult to overcome. Whereas the insertion of copper could reduce these stresses and provide greater heat transfer, the economics of this solution are doubtful. Bimetallic copper-steel receivers have been proven to be superior to steel receivers particularly in low power applications (1 – 60 kWe), where stratification is unavoidable [29]. Where tilted troughs have been used they have proved unsuccessful and unnecessary to achieve direct steam generation [30].

Many of the environmental effects restricting the development of solar thermal power stations are similar to those of other conventional power stations. However, locations that are usually suited to solar applications, such as deserts and steppe areas, tend to be away from populated areas, with plenty of available land. Although the accessibility of water can be a problem which goes in hand with some of these places, solar thermal systems generally use less water in comparison with other conventional power stations. The water requirement is heavily dependent upon the entire plant cycle being used rather than the collector type alone. With the land and water availability being very dependent on to the proposed location, the type of collector most suited for the implementation of a solar thermal plant may vary [21]. While collectors may typically use around only a third of the land covered, it is difficult to use the ground for anything else, unlike with wind turbines which can have crops growing among them. It is claimed however that the SEGS plant use no more land than conventional power plants when the full fuel cycle land requirements are considered [31].

2.2 Heliostat Field Collector (HFC)

Heliostat field collectors (HFCs), otherwise known as power towers, use an array of heliostat mirrors to direct solar rays onto a central receiver. These mirrors can be flat or slightly concave. Typically, water-steam has been used at the receiver, but some more recent systems use a molten nitrate salt. The benefit of the molten salt is that the solar receiver can be started quickly as it is a single phase fluid and the system is well suited to heat storage. Designing the tower to be oversized in comparison to the generator enables storage of excess heat. The majority of data on HFCs come from the demonstration projects, Solar 1 and Solar 2, constructed in the Mojave Desert. The Solar Tres Tower in Andalusia, Spain, is a more recent development that aimed to build upon the Solar 2 project and become the first commercial molten salt power tower system. Spain is also home to the world's first commercial water-steam power tower PS10 and has the world's largest solar tower, PS20, currently in development near Seville. However, several other pilot test facilities around the world have been built and remain in operation.

Such HFC systems are usually large at over 10MW as they benefit from economies of scale. The use of a central receiver means that minimum thermal transport is required giving higher optimal temperatures of around 500ºC [31], and stagnation temperature in the region of 1750ºC [18]. This can represent a technical challenge with thermal fatigue limiting the level of solar flux that can be sustained. The Solar 1 tower operated at 516 ºC with an outlet pressure of 105 bar, which are typical design parameters for all HFCs [20]. Typical concentration ratios range between 300 – 1500 [18, 32]. With the higher temperatures, the result is that these systems have the capacity for greater efficiencies, giving more output than the more commonly employed parabolic trough. The parasitic loads are estimated to be around 10% for a full scale system, with values being considerably higher in the non commercial Solar 2 plant, due to the lower capacity factor, at over 20% [33].

The capital cost of these system is considerable at around 4000 \$/kW or 476 \$/m^2 and with operational and maintenance costs of 0.034 – 0.093 \$/kWhe [20, 34]. As most of the cost comes from the expensive heliostats, significant effort has gone into reducing the cost of these components over the years, and by making them progressively larger, the cost has now fallen from approximately 1000$/m^2 to 150 $/m^2. It is predicted that the cost for a large central receiver system could fall as low as 2500$/kW [20, 25, 35].

From an environmental perspective, the nature of a heliostat array layout requires a large amount of space and therefore HFCs use more land than any other CSP technologies at around 4.6 m^2/MWh/year [34]. Depending upon the layout and location, factors such as the optical efficiency, capture efficiency and acceptance angle are variable [36]. The type of terrain available is also variable, while levelled ground is the most common choice, hillsides have also been utilized [37].

A number of other types of receivers have been conceived as well. In 1987 the CESA-1 tower at the Plataforma Solar de Almería in Spain used an air receiver with operating temperatures of up to 1000ºC at 10 bar with the use of ceramic receivers [18, 20]. Problems arose from the ceramic receivers having to be 20 - 25 times larger than a molten salt receiver, making the system very expensive and subject to high heat loss. A newer idea is to create a three dimensional volume that came to be known as the volumetric air receiver. In spite of its theoretical advantages, technical limitations have, as yet, restricted any large scale developments of the technology. Solgate, erected in the CESA-1 tower, is one of the few volumetric air receiver pilot projects in existence and has achieved operating temperatures of over 1000 ºC with the direct drive of a gas turbine [21]. A comprehensive description of all the power tower projects and types of receivers has been presented by Goswami and Kreith [26].

2.3 Linear Fresnel Reflector (LFR)

The linear Fresnel reflector (LFR) acts as a broken up parabolic trough made from inexpensive flat or low profiled mirrors. The central receiver is separated from the reflector field and stationary; this also reduces costs as the use of flexible and rotating high pressure components are avoided, unlike in other solar thermal technologies. To optimize the land usage and reduce shadow effects the tower height can be increased, but this can be expensive. Alternatively, a relatively new design known as the Compact Linear Fresnel Reflector (CLFR) has been developed whereby two receivers can be used with interleaving mirrors. This design claims to provide the most efficient use of land out of all the solar thermal technologies at around 1.6 hectares/MW or 1.8 m^2/MWh/year; however CLFR systems do require that the ground is level with a slope tolerance of less than 1 degree [38]. Moreover the high number of segmented mirrors means that a more complex control system is required to operate the large number of drives, which has been given as the reason that the system has not be used on a major scale [21]. However, a comparatively good half acceptance angle of 0.75º can be achieved, and the closeness of the structure to the ground makes construction and maintenance easier [39].

Due to optical, gap, and shadow losses, efficiencies are less than for the PTC, although the use of a compound parabolic collector at the receiver can improve overall optical efficiency to around 65 – 70 % [40] and the capture efficiency to 76% [41]. These systems are stated to operate at only 150ºC [39], but with the use of a secondary concentrator temperatures of 300ºC [40] at pressures of 80 bar [42] can be reached. The configuration of evacuated receivers with secondary concentrators can have a significant impact on the potential power achievable. The lower temperatures are attributed to the lower concentration ratio, which is in the region of around 30 [42]. Receivers can also be protected more easily than the PTC receivers making them a practical alternative to linear PTCs with capital and maintenance cost significantly lower [40]. Capital costs of the system are approximately 234 $\$/m^2$ [41].

2.4 Parabolic Dish Reflectors (PDR)

The Parabolic Dish Reflector (PDR) or Dish Engine is a concave mirror that focuses sunlight onto a single point receiver. Mirrors can be facetted segmented surfaces or a single parabolically shaped surface made in some forming process. The mounting structure will then depend upon the type of mirrors used. The system requires continuous two-axis tracking as the concentrated solar rays are focused onto a receiver at the single focal point. Stirling engines are the most common receiver used; however PV modules, heat pipes, micro turbine and other engines have been considered [21].

Technically, dish engines have the greatest potential, with one PDR holding the world record for solar to electrical efficiency at 31.25% [43]. With the 2-axis tracking mechanism Dish Engines allow the highest capture of the solar energy, with optical efficiencies of up to 94%, and concentration ratios ranging from 500 – 2000. For a concentration ratio of 500 the stagnation temperatures would be in the region of 1285ºC[18]. With the correct materials, temperatures of over a 1000ºC can be reached [31]; common operating pressures for these temperatures would be between 40 – 200 bar [21]. One proprietor of a 25kW Dish Engine claim that their system focuses around 60000kWh/year, and in a good desert location can be situated with one dish for every 500m^2 equating to an average power of 14 W/m^2 [44].

Even though the dish system has the greatest potential efficiency, the problem remains of finding a reliable, inexpensive and efficient engine for the system. PDRs using as Stirling engine typically have had the highest cost of electrical production, and difficulties with hybridization and heat storage. The capital costs of prototype dish systems have been as high as 12600 \$/kW, with more recent designs costing 9000 \$/kW; however large scale purchases could reduce the price to 2000 \$/kW [45]. Dish Engines do have the benefit of being modular in regards to having the capability to come in all sizes so can be useful in small and off grid applications. Another benefit of the dish is that unlike other solar thermal systems, completely level ground is not a requirement [43]. Ground usage for the world's largest proposed CSP plant in California made by SES (Solar Energy Systems) can be calculated at 4.15 m^2/MWh/year; however permits have yet to be obtained [46].

Mirrors are a major contributor to the high expense of these systems, costing around 80 - 150 \$/m^2. An alternative method that has been used on some pilot projects is to use a stretched aluminium silvered polymer, which can be considerably cheaper at around 40 – 80 \$/m^2 [47].

2.5 Linear Compound Parabolic Collector (CPC) and Fresnel Lenses

The 2 dimensional linear Compound Parabolic Collector (CPC) is considered in this review. The CPC is a non-imaging concentrator. Compared to imaging concentrators such as the parabolic trough or dish, they accept radiation over a wider range of approaching angles for a given concentration ratio. A typical configuration has a lower circular portion and an upper parabolic section to form a trough with an absorber pipe located at the bottom [48]. However, this type of design tends to be large, hence truncated CPCs are often used instead; only a slight reduction in concentration results from a one-third decrease in height [49-51].

The advantages of CPCs is that they can achieve some concentration without any form of tracking with half acceptance angles of over 20º; however this permits only a very low concentration ratio of around 3 [19]. The aim with solar thermal systems is to have a device that will operate at higher temperatures and efficiencies, which requires much higher concentration ratios than this. Due to the impractically large size of a conventional CPC for concentration ratios above 10, an alternative approach is to use a lens in front of the collector's aperture entrance. These are then referred to as primary and secondary concentrators respectively. To reduce the size and weight of the lens, a Fresnel lens, either linear or circular, would usually be selected [49]. The advantage of refractive materials, such as polymethylmethacrylate which is often used to make Fresnel lenses, is that they are generally cheaper and have a longer lifespan than reflective materials used to make mirrors [52]. For the secondary concentrator again relatively cheap materials such as aluminium or glass can be used. Furthermore, if a material is chosen that has some flexibility, a less rigid frame is required to withstand wind loads without risk of fracture.

Lenses can be used in solar applications to create either an imaging or non-imaging system. Imaging systems require very accurate 2-axis tracking to create an exact image of the light source on a receiver. However, tracking inaccuracies and manufacturing process errors can make it difficult to successfully implement lenses in this way for solar concentrators. Therefore non-imaging arrangements, using the CPC or similar types of non-imaging secondary, are often preferred and can be competitive with other types of collectors [53].

For a linear Fresnel lens-CPC arrangement to achieve temperatures of up to 200ºC, the half acceptance angle would have to be reduced significantly to around 3º as compared to static non-imaging CPCs. The benefit of this is that, although a tracking system would still have to be used, the comparatively wide tracking error margin means a simpler clock mechanism may suffice, rather than a sensor or programmed based mechanism. A flat Fresnel lens located grooved side facing down and smooth surface up is usually preferred by most designers. The lens protects the receiver from environmental damage without collecting dirt in its grooves making maintenance far easier. However, high surface reflection losses and large off-axis aberrations are found from this configuration. For these reasons curved linear Fresnel lenses are often considered which can help overcome these disadvantages through prism minimum deviation at each refractive surface [54]. Although only comparatively low operating temperatures are achievable with a concentration ratio of up to 20 with single axis tracking around a polar axis [55], and low capture efficiencies of up to 50% [56], and optical efficiencies of 60 – 65%, the capital and operational costs are reduced significantly compared to other solar thermal technologies. For a linear lens, tracking has to follow a north-south alignment due to the shortening of the focal length from off-meridian rays. For a linear lens with a 2-axis tracking system, higher concentration ratios of up to only 70 can be achieved. A single axis tracking compound parabolic collector with focusing linear Fresnel lens is predicted to cost in a similar region to the CLFR at 260 $\$/m^2$. For temperatures greater than 200ºC, Colleras Pereira recommends that a circular lens be used; however these are beyond the scope of this review [49].

2.6 Output of literature review

The literature review has identified the main technology alternatives and sub-alternatives to be the parabolic trough collector with synthetic oil or direct steam generation, the Heliostat field collector with either a water-steam, molten salt, or volumetric air receiver, the linear

Fresnel reflector or compact linear Fresnel reflector, a parabolic dish reflector combined with a Stirling engine, and finally a compound parabolic collector with or without a linear Fresnel lens.

It has also revealed the detailed criteria deemed necessary to compare the different technological alternatives, as summarised in Table 1. Where data has been unattainable, judgement has been used as the AHP dictates. Values have been listed under the three sections of technical, financial and environmental. Values for the ideal conversion and collector efficiency have also been included from the idealised thermodynamic analysis of the different collectors (see Electronic Annex 1 in the online version of this article). The criteria and alternatives in this table can be developed into a decision hierarchy tree (see Fig 2a-d), which forms the first part of the AHP study. The tabulated values can then be used to complete the pairwise comparison mathematical model (see Electronic Annex 2 for sample calculations and Annex 3 for full workings).

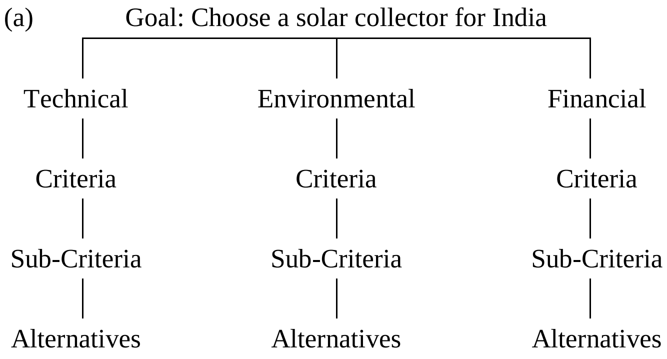
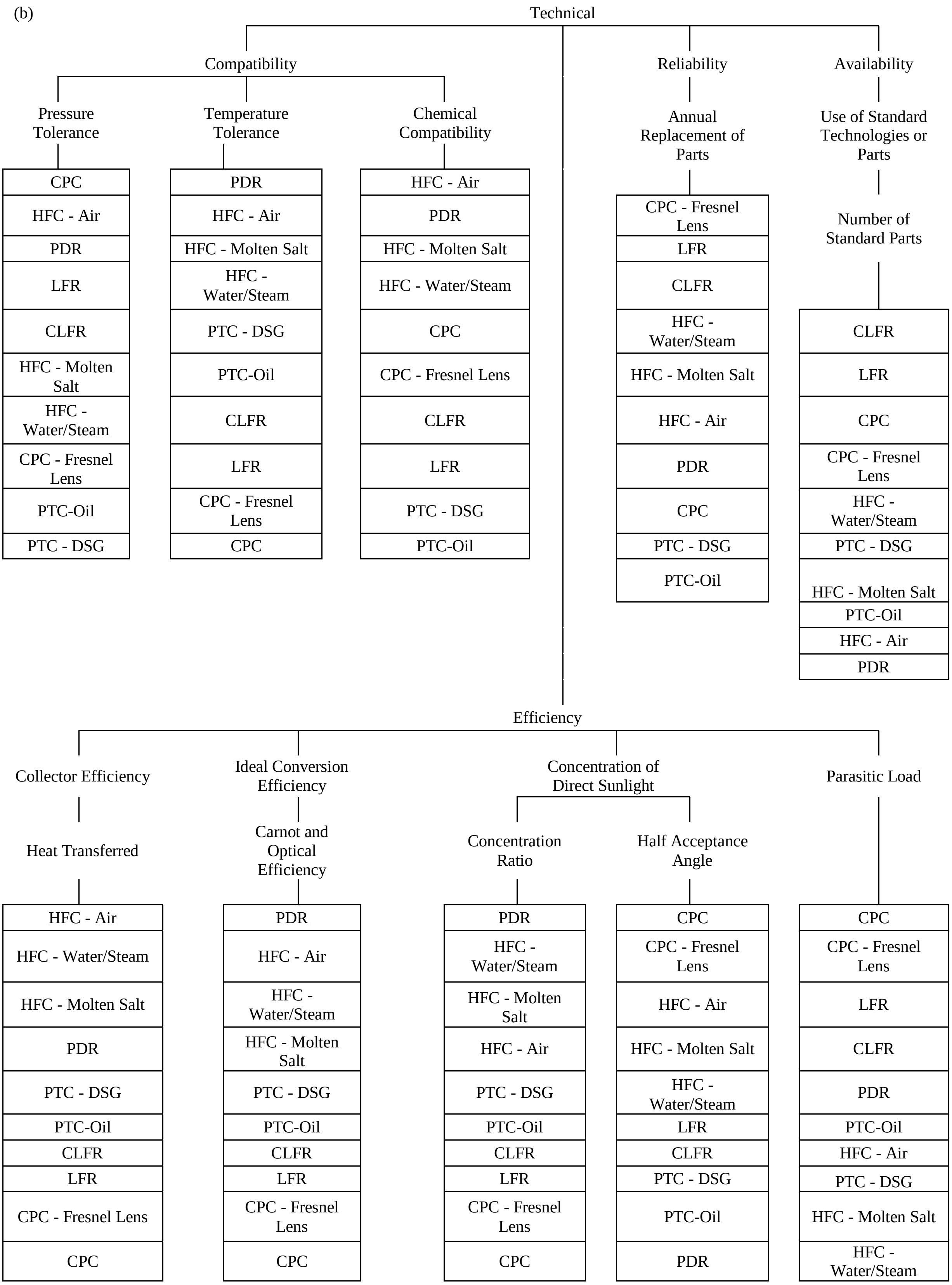


Fig 2a–d: Decision hierarchy tree for selection of a suitable solar thermal collector for Gujarat (a) with the expanded hierarchy tree for the technical criteria (b), environmental criteria (c), and financial criteria (d), showing the technologies ordered on preference for each sub-criterion, using the characteristic values (Table 2.5) from the literature review.



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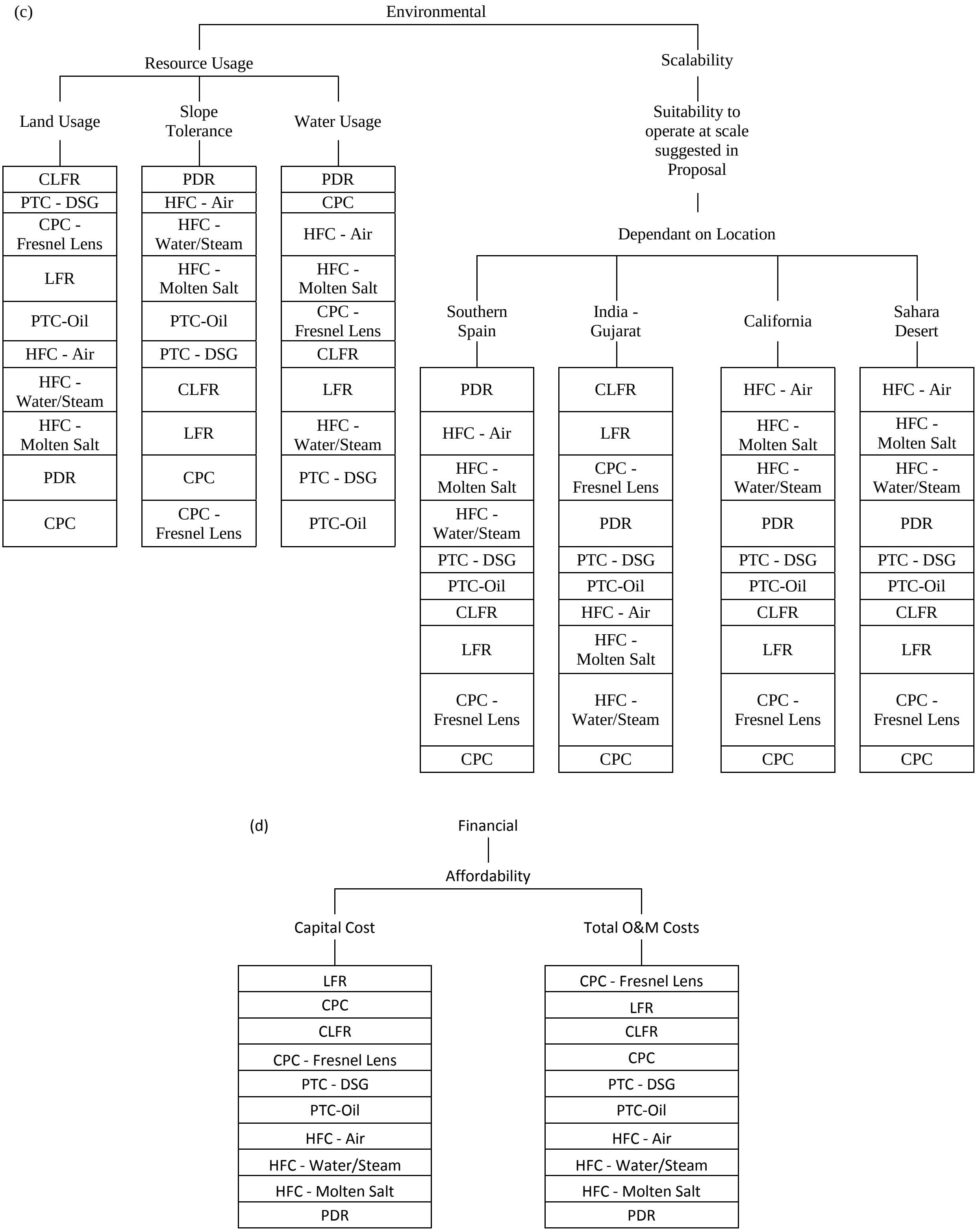


Fig 2: (*continued*).

Table 1: Characteristic values for solar thermal technologies and their alternatives, under the criteria of; technical, financial, and environmental, developed from the literature review.

					Alternatives	**Parabolic Trough**		**HFC**			**LFR**		**PDR**	**CPC**	
					Sub- Alternatives	Synthetic Oil	DSG	Salt Receiver	Water /Steam	Volumetric	CLFR	LFR	Glass	CPC	with Fresnel lens
	Criteria	**Sub criteria**	**Metric**	**Unit**	**Comment**										
Technical	**Efficiency**	Ideal Conversion Efficiency		%	Optical, and Carnot efficiency	33%	Higher	45%		Higher	25%	Lower	65%	Lower	22%
		Collector Efficiency		%	Heat transferred based on the ideal system	63%		72%			36%		66%	36%	
		Stagnation temperature		°C		600	Higher	1750		* [a]	300 +		1200 +	*	*
		Optical Efficiency		%	Ratio of sunlight capture to incident sunlight	80		Varied		73	67	Lower	94	*	60 - 65
		Concentration of direct sunlight	Concentration ratio	-		30 - 100		300 - 1500		Lower	30+		500 - 1500	3	10 to 20
			Capture efficiency	%		91		Varied		*	76	Lower	100	*	40 - 50
			Half Acceptance Angle	Degrees	Affects required tracking accuracy	0.5		*			0.75		0.4	20	3
		Parasitic load	Fraction of electrical output	%	E.g. for tracking, pumps, etc.	10	Higher	10 - 20		10	Higher	Low	4	Very low	2.3
	Compatibility with working fluid	Pressure tolerance		bar	Flexible hosing, fixed receiver	40 - 100		100+		10 -20	69		20	*	
		Temperature tolerance		°C		100 - 400	Higher	150 -800		1000+	100 - 300		500 - 1500	<100	< 200
		Chemical compatibility of heat transfer medium			Freezing, fire hazard, corrosion	Synthetic Oil	water	Molten Salt	Steam	Air	Water		Air	Water	
		2-phase flow			Are difficulties with 2phase flow encountered	No	Yes	No	Yes	No	Yes		No	Yes	
	Reliability	Reliability		% /Prediction	Environmental Resistance, Annual Replacement of Parts	5.5 - V.Low		Medium			Medium		Med - Low	Low	High
	Availability	Use of standard technologies or parts	Number of standard parts			Med - Low	Medium	Med - Low	Medium	Med - Low	High		Very low	High	Med - High
Financial	**Affordability**	Capital cost		Dollars/kW		3972	2300	4000+			-	Lower	12578	Lower	-
				Dollars/m^2		424	Lower	476			234	Lower	-	Lower	260
		Total M&O cost		Dollars/ kWh_e		0.012 - 0.02	Lower	0.034			Low	Lower	0.21	*	
Environmental	**Resource usage**	Land usage		m^2/MWh/ year	Land used per energy output	3.2	Lower	4.6			1.8	Higher	4.15	*	
		Tolerance of slope		Degrees		<1		Flexible			<1		Flexible	level	
		Water usage	Dependant on System	m^3/MWh_e	Water cooled	3.07	*	2.27	Higher	*	*		None	*	
					Dry cooled	0.3	Higher	*	Higher	*	0.04		None	*	
				m^3/m^2/year	Water mirror washing	0.022		0.022			0.022		0.022	*	Lower?
	Scalability	Efficiency at different scales	At the scale suggested in the proposal		The proposal suggested in scenario	Better		Poor			Better		Better	Better	
		Suitable operating range	Electrical Range	MW		0.05-100		0.5-100			0.05-100		0.025-100	*	

[a] Due to the prototype nature of some of these systems were data is not currently widely available or known values are represented with a '*'.

3. AHP Workshop and Analysis

Four case study scenarios were proposed to a panel of ten experts working in various fields within the Solar Energy Centre. Located at Gurgaon, Haryana, the Solar Energy Centre was built in 1991 to extend research into varying solar technologies. It is recognised by India's Ministry of Non-conventional Energy Sources as a centre for the testing and evaluation of solar based devices [57]. Due to its nationally and internationally acknowledged expertise, the centre was chosen for this AHP workshop.

A presentation explaining the purpose of the AHP study was delivered followed by a synopsis for each of the different case studies. These synopses were presented to the panel in written form also. They included information about each region's climate and topography, along with the policy setting and government legislation that exist to promote renewable projects. Demographic factors were also mentioned, as was the probable scale of a solar thermal power plant in these areas (see Electronic Annex 4 in the online version of this article).

Firstly, the experts were given the opportunity to expand or reduce the list of criteria that had been developed from the literature review given. However, in this case no sub-criteria were added or removed. The experts were then asked to score the criteria from 1 to 10, for each of the case studies. The pairwise comparison could then be completed to determine the criteria weighting vectors (see Electronic Annex 5 in the online version of this article). Thus the combination of the literature review (which gave the priority vectors) and the experts' opinions (giving the weightings) enabled the analysis to be completed following the standard AHP methodology [58].

4. Results and sensitivity analysis

The bar charts of Figure 3 gives the results for the four cases studies, in terms of percentages which indicate relative levels of preference for each technology. For Gujarat, the preferred technology is the linear Fresnel lens-CPC which scores 11.9%. The compact linear Fresnel reflector at 11.5% was a close second.

These results for Gujarat arise from the high weighting given by the panel to the criteria of good reliability, low cost and low ground usage for this location. For the other regions, the study gives very different recommendations. Thus, with a score of 13.5%, the parabolic dish reflector is preferred for the Sahara Desert. For the large scale implementation assumed in this case study, the technical capabilities of the system were weighted as the most important criteria, thus favouring the PDR due to its superior technical efficiencies. Surprisingly, the PTC using synthetic oil receives an unfavourable rating of only 5.9%. Another factor favouring the PDR is water usage, which for a system in a large desert like the Sahara is crucial; the PDR with a Stirling engine has a very low water usage whereas the PTC with steam turbine has a high usage.

The Heliostat field collectors and PDR are highly favoured for both the Mojave Desert and Southern Spain. In the Mojave Desert the volumetric air receiver power tower is strongly favoured at 14.2%, with the PDR a close second at 13.9%. A similar result profile is found for southern Spain except with regard to the PTC which is less favoured than in the Mojave Desert.

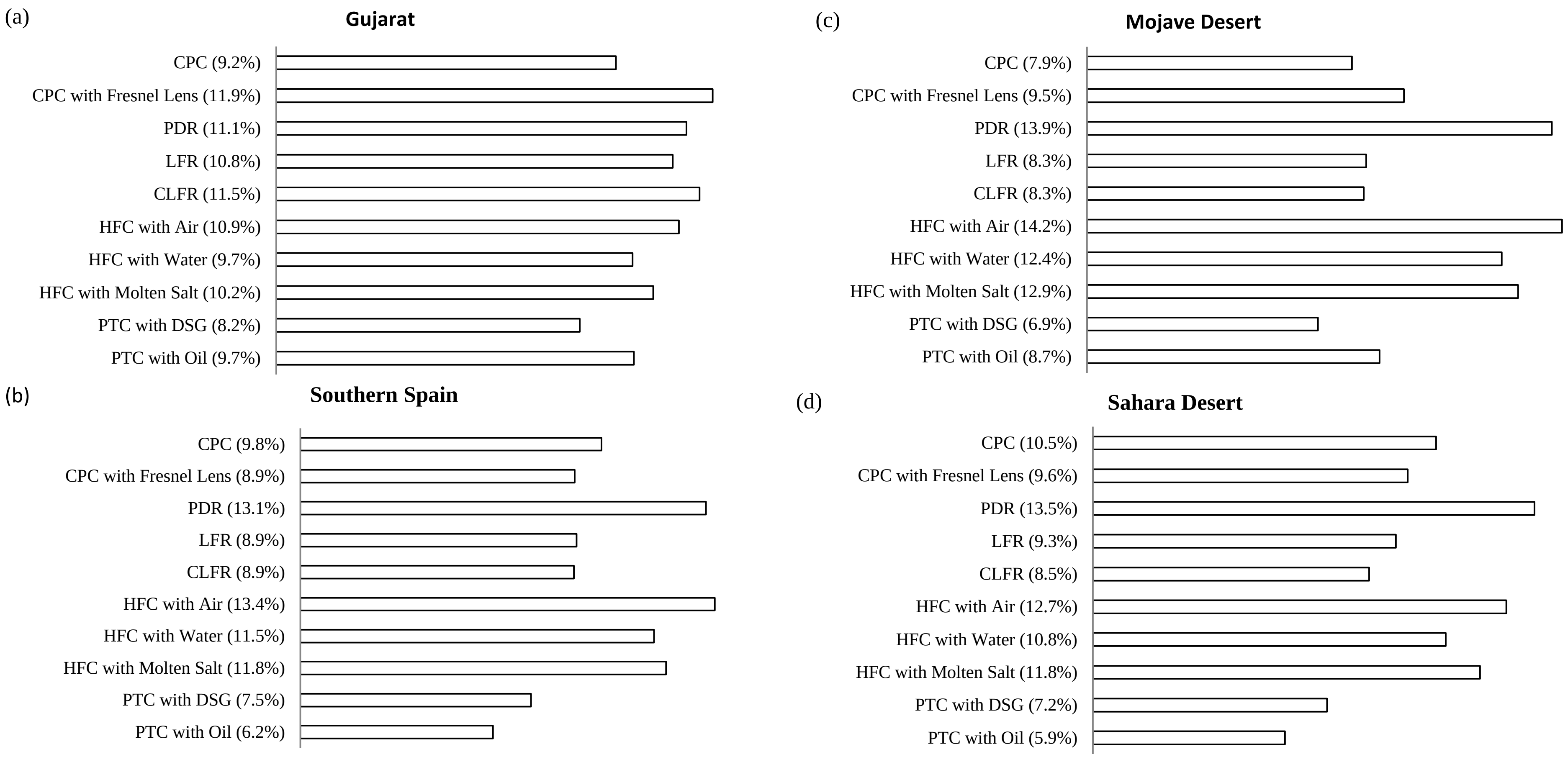


Fig 3a-d: Final results from the AHP study showing each solar thermal collector's percentage preference for Gujarat (a), Southern Spain (b), Mojave Desert (c) and the Sahara Desert (d).

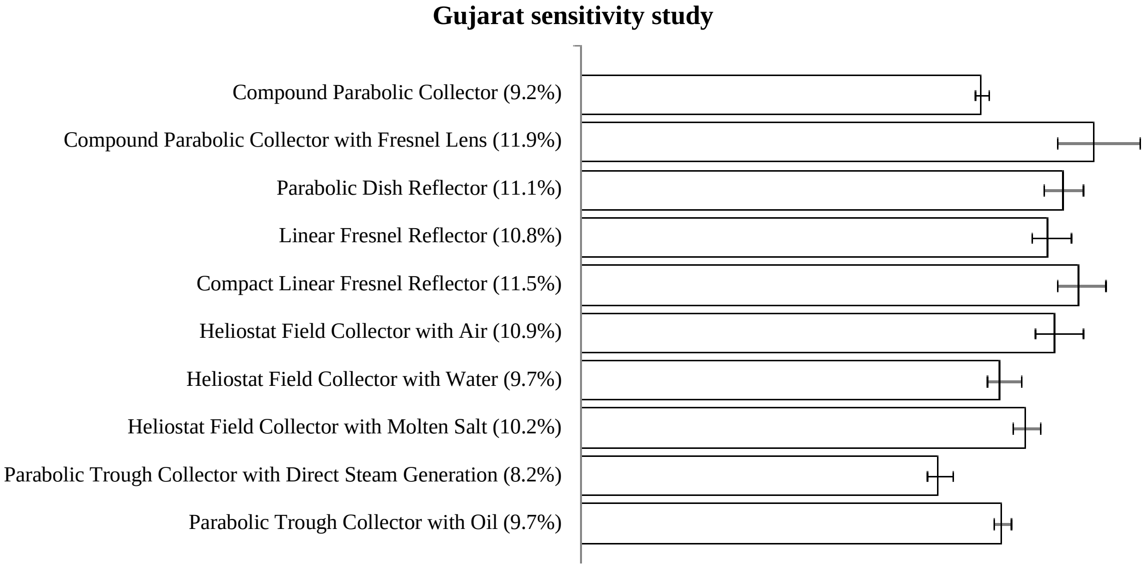


Fig 4: Sensitivity study for Gujarat showing the potential range of the percentage preference for each alternative.

For Gujarat, which was the main focus of this paper, it was noted that the AHP study resulted in very close comparisons among alternatives. Therefore a sensitivity analysis was carried out to investigate the significance of the differences (see Fig 4). The three top-ranking criteria (collector efficiency, ideal conversion efficiency, and capital cost) were varied by adding or subtracting 1 to the experts scoring for each one, thus altering the weighting given from the pair-wise comparison matrix.

The effect of decreasing the top three weighted criteria re-ordered the criteria so that the importance of the maintenance costs, land usage, and reliability increases; meanwhile the ideal conversion efficiency and capital cost moved down the weighting order. This has the effect of increasing the percentage preference of the Fresnel lens-CPC to 12.9%.

In contrast, increasing the weighting of the top three criteria did not change the order, but it still had a substantial effect on the results. With the ideal conversion efficiency and collector efficiency weighting increased, the more technically efficient PTC became favoured against technologies like the linear Fresnel lens-CPC and CLFR.

5. Discussion

The variation in the results among the four regions merits further discussion about each technology. Aspects of how the study was conducted may have influenced the outcomes and it is therefore worth reviewing what has been learnt about the process in order to guide future studies of this kind

The PTC, despite being the most widely adopted technology, is not especially strong against any of the criteria used in this study. On the other hand, the very fact that the PTC is well established could distort the results, because the data and opinions about them are the consequence of many years of operational experience; whereas for other technologies the information available sometimes has to be based on prototypes or theoretical estimates aimed at promoting the technology. Comparisons based on expected values stated for newer or yet-to-be-implemented systems have to be judged carefully.

The PDR fares very favourably in all four case studies. With the highest weightings for all four case studies given to the ideal conversion efficiency and collector efficiency, the PDR immediately gains an advantage with its greater operational efficiencies in comparison with the other technologies. Power towers have been pioneered in both Spain and California; however, the volumetric air receiver is a technology that has not been used as much as other types of receivers. Again this suggests that the model is biased towards operational capabilities rather than reliability and market establishment. While there is danger of making over-optimistic assumptions about future technological advancements, it is also important not to model a scenario that will only ever produce well established existing technologies as the answer, as this might result in technology choices that are too conservative.

The variability in the results for the different regions is attributed primarily to the importance given to the cost criterion for India, with the cheaper technologies, Fresnel lens-CPC and CLFR, ranking highest in the final group order. The larger commercial-scale technologies being more suitable for the economically developed countries of Europe and America, with the HFC ranked first. The water usage in the Sahara desert, governing that the PDR, which uses the smallest amount, ranked top. As a whole, greater confidence may be given to the AHP results for Gujarat than for the other 3 regions due to the make-up of the expert panel.

The number of experts consulted in this study was 10. With a panel of different size or make-up, the outcomes may have been different. This type of uncertainty applies to all AHP or similar decision-making processes. While no literature is known that defines the exact number of experts to consult, taking into account a greater amount of expert opinion will benefit the process. However, a larger panel will make workshop facilitation and resolution of conflicts more difficult. In practice, experience indicates that limiting the panel size stimulates participation and contribution, leading the group to a consensus [59]. Moreover, once an overall result has been produced the whole process can be examined and refined with further opinion taken into account.

The AHP process does suffer from several other known drawbacks: subjectivity can never be reduced to zero and the AHP does not necessarily highlight poor judgements [60, 61]. In addition, the AHP cannot guarantee the independence of the results with regard to the inclusion of an irrelevant alternative. An ideal decision-making process should be unaffected by such alternatives; however in practice this is often violated in AHP [62]. The consequence for this study is that the pre-selection process, whereby the experts were not presented with all possible technologies but a shortlist based on the judgement of the authors, may in principle have affected the outcome. We note however that even the weakest technology considered (the CPC without Fresnel lens, which ranked very poorly against certain criteria) did not rank poorly against all criteria; therefore there was no irrelevant alternative as such. Nevertheless, the fact that this technology is unlikely to be considered a viable choice by any expert leads the authors to believe that it would be better to exclude it from any re-run of this study.

Another area of improvement relates to the choice of criteria. Although the expert panel declined to change the criteria or alternatives chosen when given the opportunity to do so, the authors consider that inclusion of ‘market establishment’ or ‘internal rates of return’ as explicit criteria would be an improvement to the model.

Despite the several well-researched challenges facing the AHP, it remains the most popular among MCDM techniques. The review by Pohekar and Ramachandran, of MCDM techniques applied to sustainable energy planning, demonstrates how AHP is favoured over other MCDM methods based on the numbers of publications in each field. These methods include Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), the Elimination and Choice Translating Reality (ELECTRE), Multi-Attribute Utility Theory (MAUT) and several other methods [10]. Wallenius et al. provide evidence through publication history, that research via the use of the AHP is greater than that of other MCDM techniques and other decision-making methods such as Multi-Objective

Decision-Making (MODM). Between 2000 and 2004 there were nearly 450 publications relating to the AHP, MAUT had only 250. The use of MODM methods demonstrated considerable growth through Evolutionary Multi-objective Optimization (EMO) with 330 publications. Other MODM methods such as Goal Programming and Math Programming had substantially fewer with less than 250 and 150 publications respectively [63]. This trend in publication history indicates a significant preference towards AHP over other decision-making models. These different decision-making techniques are not necessarily in competition with each other, and integration of methods could be complementary as it would remove any shortcomings associated with each one. An integrated Goal Programming – AHP model has been recommended, particularly in the field of energy where quantitative and qualitative criteria are incorporated into the analysis [13]. Further work on the integration of MCDM and MODM techniques would be the next logical step for their application in the field of solar energy.

On a final note, it is worth observing that the results of the study may also be used to infer how much more people may be willing to pay for improvements in certain criteria. This can be obtained from the AHP weighting vectors, and the characteristic table of values, for the different alternatives. For example, the attributes and weightings for the LFR and PTC can be used to determine the value, in terms of the capital cost, for an improvement in the ideal conversion efficiency and concentration ratio. A swing from 36-63% for the LFR to the PTC is seen for the ideal conversion efficiency, implying a value of 224 $\$/m^2$ for this increase, as these two criteria received equal weighting from the panel. However the value (in capital cost) for an improvement in the concentration ratio is worth less as seen from the different weightings given. With the capital cost receiving nearly twice the weight given to the concentration ratio, the increase in concentration ratio from the LFR to the PTC is worth only

131 \$/m^2. In a future study these findings could be confirmed with the help of a separate questionnaire designed explicitly to enquire about the monetary values placed by the experts on such technical improvements.

6. Conclusion

The AHP study indicates that the preferred solar collector for the case of Gujarat in north-west India is the linear Fresnel lens with CPC-type secondary. After the sensitivity analysis, in which criteria weightings were varied to reflect likely uncertainties in the selection process, the preferred technologies emerging are either the Fresnel lens-CPC or the parabolic dish reflector. For the other cases of southern Spain and the Mojave Desert in California, the study indicates the parabolic dish reflector; and for the Sahara Desert it indicates the heliostat field collector with the air receiver.

These finding are unexpected in that these are not the technologies used mostly to date. In particular, Fresnel lenses have hardly been used for solar thermal power, though they are used for photovoltaic solar power. Nevertheless, this could be for historical reasons. Their potential low cost and high reliability makes Fresnel lenses worthy of further investigation and development which may be the subject of further work. It is our recommendation that the Fresnel lens-CPC and the PDR are pursued in the context of the current project in Gujarat following this study.

7. ANNEXES

Annex 1: Thermodynamic Analysis

The thermodynamic analysis of solar collectors for an idealised system is presented to compare the achievable efficiency of different collectors based on consistent assumptions. The calculations provide numerical values for the ideal conversion efficiency, and collector efficiency criteria. Similar approaches have been used before, and further detailed analysis of the entropy and non-isothermal properties of the system can be found elsewhere [18].

For a collector of aperture area A_a receiving irradiance, q^* (W/m^2), the solar radiation rate Q^* (W) is given by,

$$Q^* = q^* A_a \tag{1}$$

For a concentrating system, the optical efficiency is defined as the ratio of the energy absorbed by the receiver to the energy incident on the collector aperture. The optical efficiency takes into account tracking accuracy error, and optical errors, which includes the optical properties of the receiver, and the mirror's reflectance. With the optical efficiency η_0, the radiation falling on the receiver can be found.

$$q_0^* = \eta_0 q^* \tag{2}$$

The power delivered via heat transfer, Q, is a function of the net solar radiation rate minus the ambient heat loss at the receiver, Q_0.

$$Q = Q^* - Q_0 \tag{3}$$

$$Q_0 = U_r A_r (T_r - T_0) \tag{4}$$

Where U_r is the overall heat transfer coefficient, A_r the area of the receiver, T_r the temperature of the receiver and T_0 the ambient temperature.

The collector efficiency, η_c can therefore be calculated as,

$$\eta_c = \frac{Q}{Q^*} = \frac{\eta_0 q^* A_a - U_r A_r (T_r - T_0)}{\eta_0 q^* A_a} \tag{5}$$

A parameter often quoted for solar thermal collectors is the concentration ratio, *C*, which is the area of the collector aperture divided by that of the receiver.

$$C = \frac{A_a}{A_r} \tag{6}$$

Another factor that can be deduced is the stagnation temperature $T_{r,max}$, which occurs when all the incoming solar radiation is lost to ambient heat loss. This can be measured by stopping the fluid running through the receiver pipes and noting the maximum temperature reached.

$$\frac{T_{r,\max}}{T_0} = 1 + \frac{Q^*}{U_r A_r T_0} \tag{7}$$

Therefore from these equations the overall heat transfer coefficient can be calculated

$$T_{r,\max} = T_0 + \frac{\eta_0 q * C}{U_r}$$

$$U_r = \frac{\eta_0 q * C}{T_{r,\max} - T_0} \qquad 8$$

The maximum possible efficiency of the system can also be estimated based on the Carnot cycle.

$$\eta_{Carnot} = 1 - \frac{T_0}{T_r} \qquad 9$$

The multiplication of the optical and Carnot cycle efficiencies represents the ideal conversion efficiencies of the collector system.

$$\eta_{tot} = \eta_{Carnot} \eta_0 \qquad 10$$

The theoretical overall efficiency of the system assuming conditions for an isothermal collector can also be calculated.

$$\eta_{Overall} = \eta_0 \eta_c \eta_{Carnot} \qquad 11$$

It can therefore be concluded that for any ideal receiver, operating at a known concentration ratio, the optimum receiver temperature is [18, 26].

$$T_{r,opt} = \sqrt{T_{r,\max} T_0} \qquad 12$$

Annex 2: Example Calculations

The criteria for the AHP are derived from the functional requirements and product characteristics. From the literature review, the technological alternatives relating to solar collectors have been assessed in terms of their technical, sustainable, and financial viability, to develop a series of sub problems to be analysed.

Table 2.1

Sub criteria selected for the AHP study.

TECHNICAL	
Efficiency	Ideal Conversion Efficiency
	Collector Efficiency
	Concentration Ratio
	Half Acceptance Angle
	Parasitic load
Compatibility with working fluid	Pressure Tolerance
	Temperature Tolerance
	Chemical Compatibility of Heat Transfer Medium
Reliability	Environmental Resistance
Availability	Use of standard technologies or parts
FINANCIAL	
Affordability	Capital cost
	Total M&O cost
SUSTAINABLITY	
Resource usage	Land usage
	Tolerance of slope
	Water usage
Scalability	Efficiency at different scales

The following solar technologies have been selected as the possible solution alternatives based on the review.

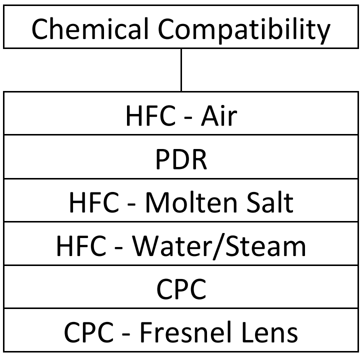
Table 2.2

List of the solar technology alternatives used in the AHP study.

Solar Technology Alternatives	**Acronym**
Parabolic Trough using Synthetic Oil	PTC - oil
Parabolic Trough with Direct Steam Generation	PTC - dsg
Heliostat Field Collector with a Water/Steam Receiver	HFC - H20
Heliostat Field Collector with a Molten Salt Receiver	HFC - salt
Heliostat Field Collector with a Volumetric Air Receiver	HFC - air
Compact Linear Fresnel Reflector	CLFR
Linear Fresnel Reflector	LFR
Parabolic Dish Reflector	PDR
Compound Parabolic Collector	CPC
Fresnel Lens with a Secondary Compound Parabolic Collector	CPC - fl

By way of example, the method for the AHP analysis is now discussed and partially demonstrated for the chemical compatibility criteria.

An order of preference for each criterion is first established, and a decision hierarchy tree is developed. Data obtained on each collector is used to determine the favoured order for the decision tree and judgment or expert opinion is used where data is unavailable.



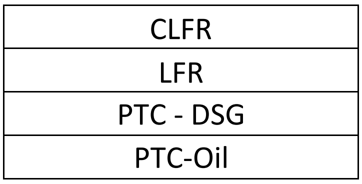


Fig.5. The Decision Hierarchy Tree for sub criteria chemical compatibility.

To establish how much a certain collector is favoured over another for a given criterion, priorities are ascertained to develop the Pairwise Comparison Matrix. Judgment of preference is selected on a scale of 1 to 9.

Table 2.3

Pairwise comparison scale values for the level of preference to be used in the pairwise comparison matrix.

Pairwise Comparison Scale

Verbal Judgment of Preference	**Numerical Rating**
Extremely Preferred	9
Very strong to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

The Pairwise Comparison Matrix is a mathematical process which orders the decision tree into a matrix for the comparison scale to be applied.

Table 2.4

Pairwise comparison matrix showing how preferred each alternative is in terms of their chemical compatibility.

	HFC-air	PDR	HFC-salt	HFC-H20	CPC	CPC-fl	CLFR	LFR	PTC-dsg	PTC-oil
HFC-air	1	1	2	3	3	3	3	3	5	5
PDR	1.00	1	2	3	3	3	3	3	5	5
HFC-salt	0.50	0.50	1	2	2	2	2	2	4	4
HFC-H20	0.33	0.33	0.50	1	1	1	1	1	3	3
CPC	0.33	0.33	0.50	1.00	1	1	1	1	3	3
CPC-fl	0.33	0.33	0.50	1.00	1.00	1	1	1	3	3
CLFR	0.33	0.33	0.50	1.00	1.00	1.00	1	1	3	3
LFR	0.33	0.33	0.50	1.00	1.00	1.00	1.00	1	3	3
PTC-dsg	0.20	0.20	0.25	0.33	0.33	0.33	0.33	0.33	1	1
PTC-oil	0.20	0.20	0.25	0.33	0.33	0.33	0.33	0.33	1.00	1
Total	4.57	4.57	8.00	13.67	13.67	13.67	13.67	13.67	31.00	31.00

A Priority Vector for each collector in terms of capital cost is then calculated by dividing each cell by the total column value and averaging the row.

Table 2.5

Priority vectors of each alternative for the chemical compatibility.

	HFC-air	PDR	HFC-salt	HFC-H20	CPC	CPC-fl	CLFR	LFR	PTC-dsg	PTC-oil	Priority Vector
HFC-air	0.22	0.22	0.25	0.22	0.22	0.22	0.22	0.22	0.16	0.16	0.211
PDR	0.22	0.22	0.25	0.22	0.22	0.22	0.22	0.22	0.16	0.16	0.211
HFC-salt	0.11	0.11	0.13	0.15	0.15	0.15	0.15	0.15	0.13	0.13	0.133
HFC-H20	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
CPC	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
CPC-fl	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
CLFR	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
LFR	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
PTC-dsg	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.031
PTC-oil	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.031
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

This process is repeated till a priority vector for each alternative is developed for every criterion. Thus giving the preference of each alternative for ever criteria, however the importance of each criterion in relation to the other criteria is not specified. Therefore the same process is applied to develop a weighting vector for each criterion with a priority order and judgment of preference scale used again for a final pairwise comparison matrix. The final overall value for how much each technology is preferred, is calculated by multiplying each priority vector by its corresponding criterion's weighting vector and totalling the values for the corresponding technology. These weightings will however be very dependent upon the location intended for the implementation of a solar thermal system.

A consistency check can also be carried out on the pairwise matrix to access the reliability of process. The measure of consistency is expressed using the consistency ratio *CR*, which is calculated from the consistency index *CI* and random consistency index *RI* following Saaty. If the consistency ratio is smaller than or equal to 10% then the inconsistency is acceptable. The consistency index is given by:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \qquad 13$$

Where $\lambda_{\max}$ is the sum of the priority vectors multiplied by the corresponding totalled value of the pairwise matrix column, and *n* is the size of the matrix.

Table 2.6

Calculation of $\lambda_{\max}$ for the chemical compatibility sub criteria

$\lambda_{\max}$
0.96
0.96
1.07
1.05
1.05
1.05
1.05
1.05
0.95

0.95

Total 10.13

The consistency index can therefore be calculated as 0.14. From standard tables, the random consistency index is 1.45 for *n* =9. The consistency ratio can now be calculated.

$$CR = \frac{CI}{RI} \tag{14}$$

Therefore we have acceptable consistency of 0.097 or 9.7% in this case.

Annex 3: Full pairwise Comparison of Alternatives for Every Criterion

Table 3.1 Full pairwise comparison matrix for the development of the priority vectors

Pairwise comparison matrix showing preferences for the collectors in terms of Ideal Conversion Efficiency

	PDR	HFC-air	HFC-H20	HFC-salt	PTC-dsg	PTC-oil	CLFR	LFR	CPC-fl	CPC	Priority Vector
PDR	0.30	0.36	0.32	0.32	0.32	0.27	0.21	0.19	0.19	0.17	0.266
HFC-air	0.15	0.18	0.21	0.21	0.21	0.20	0.18	0.16	0.16	0.15	0.183
HFC-H20	0.10	0.09	0.11	0.11	0.11	0.13	0.14	0.14	0.14	0.13	0.119
HFC-salt	0.10	0.09	0.11	0.11	0.11	0.13	0.14	0.14	0.14	0.13	0.119
PTC-dsg	0.10	0.09	0.11	0.11	0.11	0.13	0.14	0.14	0.14	0.13	0.119
PTC-oil	0.08	0.06	0.05	0.05	0.05	0.07	0.11	0.11	0.11	0.11	0.080
CLFR	0.05	0.04	0.03	0.03	0.03	0.02	0.04	0.05	0.05	0.07	0.040
LFR	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.027
CPC-fl	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.027
CPC	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.019
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Concentration Ratio

	PDR	HFC-H20	HFC-salt	HFC-air	PTC-dsg	PTC-oil	CLFR	LFR	CPC-fl	CPC	Priority Vector
PDR	0.22	0.22	0.22	0.24	0.22	0.22	0.20	0.20	0.18	0.14	0.209
HFC-H20	0.22	0.22	0.22	0.24	0.22	0.22	0.20	0.20	0.18	0.14	0.209
HFC-salt	0.22	0.22	0.22	0.24	0.22	0.22	0.20	0.20	0.18	0.14	0.209
HFC-air	0.11	0.11	0.11	0.12	0.18	0.18	0.17	0.17	0.16	0.14	0.145
PTC-dsg	0.04	0.04	0.04	0.03	0.04	0.04	0.07	0.07	0.08	0.10	0.056
PTC-oil	0.04	0.04	0.04	0.03	0.04	0.04	0.07	0.07	0.08	0.10	0.056
CLFR	0.04	0.04	0.04	0.02	0.02	0.02	0.03	0.03	0.05	0.08	0.038
LFR	0.04	0.04	0.04	0.02	0.02	0.02	0.03	0.03	0.05	0.08	0.038

CPC-fl	0.03	0.03	0.03	0.02	0.01	0.01	0.02	0.02	0.03	0.06	0.027
CPC	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.014
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Collector Efficiency

	HFC-air	HFC-H20	HFC-salt	PDR	PTC-dsg	PTC-oil	CLFR	LFR	CPC-fl	CPC	Priority Vector
HFC-air	0.21	0.21	0.21	0.23	0.21	0.21	0.17	0.17	0.17	0.17	0.196
HFC-H20	0.21	0.21	0.21	0.23	0.21	0.21	0.17	0.17	0.17	0.17	0.196
HFC-salt	0.21	0.21	0.21	0.23	0.21	0.21	0.17	0.17	0.17	0.17	0.196
PDR	0.10	0.10	0.10	0.11	0.14	0.14	0.14	0.14	0.14	0.14	0.128
PTC-dsg	0.07	0.07	0.07	0.06	0.07	0.07	0.11	0.11	0.11	0.11	0.086
PTC-oil	0.07	0.07	0.07	0.06	0.07	0.07	0.11	0.11	0.11	0.11	0.086
CLFR	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.028
LFR	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.028
CPC-fl	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.028
CPC	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.028
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Half-Acceptance Angle

	CPC	CPC-fl	HFC-air	HFC-salt	HFC-H20	LFR	CLFR	PTC-dsg	PTC-oil	PDR	Priority Vector
CPC	0.31	0.38	0.36	0.31	0.31	0.26	0.26	0.22	0.22	0.16	0.279
CPC-fl	0.16	0.19	0.24	0.23	0.23	0.21	0.21	0.18	0.18	0.16	0.199
HFC-air	0.10	0.10	0.12	0.16	0.16	0.16	0.16	0.15	0.15	0.13	0.137
HFC-salt	0.08	0.06	0.06	0.08	0.08	0.10	0.10	0.11	0.11	0.11	0.090
HFC-H20	0.08	0.06	0.06	0.08	0.08	0.10	0.10	0.11	0.11	0.11	0.090
LFR	0.06	0.05	0.04	0.04	0.04	0.05	0.05	0.07	0.07	0.09	0.057
CLFR	0.06	0.05	0.04	0.04	0.04	0.05	0.05	0.07	0.07	0.09	0.057
PTC-dsg	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.07	0.036
PTC-oil	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.07	0.036
PDR	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.020
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Parasitic Load

	CPC	CPC-fl	LFR	CLFR	PDR	PTC-oil	HFC-air	PTC-dsg	HFC-salt	HFC-H20	Priority Vector
CPC	0.34	0.42	0.39	0.35	0.31	0.25	0.25	0.22	0.20	0.20	0.292
CPC-fl	0.17	0.21	0.26	0.26	0.25	0.21	0.21	0.19	0.18	0.18	0.212
LFR	0.11	0.10	0.13	0.17	0.18	0.18	0.18	0.17	0.16	0.16	0.154
CLFR	0.09	0.07	0.07	0.09	0.12	0.14	0.14	0.14	0.13	0.13	0.112
PDR	0.07	0.05	0.04	0.04	0.06	0.11	0.11	0.11	0.11	0.11	0.081
PTC-oil	0.05	0.03	0.03	0.02	0.02	0.04	0.04	0.06	0.07	0.07	0.041
HFC-air	0.05	0.03	0.03	0.02	0.02	0.04	0.04	0.06	0.07	0.07	0.041
PTC-dsg	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.04	0.028
HFC-salt	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.019

HFC-H20	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.019
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Pressure Tolerance

	CPC	HFC-air	PDR	LFR	CLFR	HFC-salt	HFC-H20	CPC-fl	PTC-oil	PTC-dsg	Priority Vector
CPC	0.19	0.19	0.19	0.20	0.20	0.19	0.19	0.17	0.15	0.15	0.181
HFC-air	0.19	0.19	0.19	0.20	0.20	0.19	0.19	0.17	0.15	0.15	0.181
PDR	0.19	0.19	0.19	0.20	0.20	0.19	0.19	0.17	0.15	0.15	0.181
LFR	0.09	0.09	0.09	0.10	0.10	0.12	0.12	0.13	0.12	0.12	0.110
CLFR	0.09	0.09	0.09	0.10	0.10	0.12	0.12	0.13	0.12	0.12	0.110
HFC-salt	0.06	0.06	0.06	0.05	0.05	0.06	0.06	0.08	0.09	0.09	0.068
HFC-H20	0.06	0.06	0.06	0.05	0.05	0.06	0.06	0.08	0.09	0.09	0.068
CPC-fl	0.05	0.05	0.05	0.03	0.03	0.03	0.03	0.04	0.06	0.06	0.043
PTC-oil	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.029
PTC-dsg	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.029
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Temperature Tolerance

	PDR	HFC-air	HFC-salt	HFC-H20	PTC-dsg	PTC-oil	CLFR	LFR	CPC-fl	CPC	Priority Vector
PDR	0.25	0.26	0.30	0.22	0.25	0.21	0.20	0.20	0.16	0.15	0.218
HFC-air	0.25	0.26	0.30	0.32	0.25	0.21	0.20	0.20	0.16	0.15	0.229
HFC-salt	0.12	0.13	0.15	0.22	0.19	0.17	0.16	0.16	0.14	0.13	0.157
HFC-H20	0.12	0.09	0.07	0.11	0.19	0.17	0.16	0.16	0.14	0.13	0.134
PTC-dsg	0.06	0.06	0.05	0.04	0.06	0.13	0.13	0.13	0.12	0.11	0.089
PTC-oil	0.05	0.05	0.04	0.03	0.02	0.04	0.07	0.07	0.12	0.11	0.059
CLFR	0.04	0.04	0.03	0.02	0.02	0.02	0.03	0.03	0.07	0.08	0.039
LFR	0.04	0.04	0.03	0.02	0.02	0.02	0.03	0.03	0.07	0.08	0.039
CPC-fl	0.04	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.05	0.023
CPC	0.03	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.014
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Chemical Compatibility

	HFC-air	PDR	HFC-salt	HFC-H20	CPC	CPC-fl	CLFR	LFR	PTC-dsg	PTC-oil	Priority Vector
HFC-air	0.22	0.22	0.25	0.22	0.22	0.22	0.22	0.22	0.16	0.16	0.211
PDR	0.22	0.22	0.25	0.22	0.22	0.22	0.22	0.22	0.16	0.16	0.211
HFC-salt	0.11	0.11	0.13	0.15	0.15	0.15	0.15	0.15	0.13	0.13	0.133
HFC-H20	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
CPC	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
CPC-fl	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
CLFR	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
LFR	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.10	0.10	0.077
PTC-dsg	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.031
PTC-oil	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.031

Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Pairwise comparison matrix showing preferences for the collectors in terms of Reliability

	CPC-fl	LFR	CLFR	HFC-H20	HFC-salt	HFC-air	PDR	CPC	PTC-dsg	PTC-oil	Priority Vector
CPC-fl	0.38	0.50	0.50	0.35	0.35	0.29	0.25	0.25	0.25	0.25	0.337
LFR	0.09	0.12	0.12	0.18	0.18	0.17	0.16	0.16	0.16	0.16	0.149
CLFR	0.09	0.12	0.12	0.18	0.18	0.17	0.16	0.16	0.16	0.16	0.149
HFC-H20	0.09	0.06	0.06	0.09	0.09	0.13	0.13	0.13	0.13	0.13	0.102
HFC-salt	0.09	0.06	0.06	0.09	0.09	0.13	0.13	0.13	0.13	0.13	0.102
HFC-air	0.05	0.03	0.03	0.03	0.03	0.04	0.06	0.06	0.06	0.06	0.047
PDR	0.05	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.029
CPC	0.05	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.029
PTC-dsg	0.05	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.029
PTC-oil	0.05	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.029
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Use of Standard Technologies

	CLFR	LFR	CPC	CPC-fl	HFC-H20	PTC-dsg	HFC-salt	PTC-oil	HFC-air	PDR	Priority Vector
CLFR	0.20	0.20	0.20	0.22	0.21	0.21	0.19	0.19	0.16	0.15	0.193
LFR	0.20	0.20	0.20	0.22	0.21	0.21	0.19	0.19	0.16	0.15	0.193
CPC	0.20	0.20	0.20	0.22	0.21	0.21	0.19	0.19	0.16	0.15	0.193
CPC-fl	0.10	0.10	0.10	0.11	0.14	0.14	0.14	0.14	0.14	0.13	0.124
HFC-H20	0.07	0.07	0.07	0.06	0.07	0.07	0.09	0.09	0.11	0.11	0.081
PTC-dsg	0.07	0.07	0.07	0.06	0.07	0.07	0.09	0.09	0.11	0.11	0.081
HFC-salt	0.05	0.05	0.05	0.04	0.03	0.03	0.05	0.05	0.07	0.08	0.050
PTC-oil	0.05	0.05	0.05	0.04	0.03	0.03	0.05	0.05	0.07	0.06	0.048
HFC-air	0.03	0.03	0.03	0.02	0.01	0.01	0.02	0.02	0.02	0.05	0.024
PDR	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.015
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Use of Capital Cost

	LFR	CPC	CLFR	CPC-FL	PTC-dsg	PTC-oil	HFC-air	HFC-H20	HFC-salt	PDR	Priority Vector
LFR	0.20	0.20	0.20	0.22	0.22	0.20	0.17	0.17	0.17	0.14	0.190
CPC	0.20	0.20	0.20	0.22	0.22	0.20	0.17	0.17	0.17	0.14	0.190
CLFR	0.20	0.20	0.20	0.22	0.22	0.20	0.17	0.17	0.17	0.14	0.190
CPC-FL	0.10	0.10	0.10	0.11	0.11	0.13	0.14	0.14	0.14	0.13	0.121
PTC-dsg	0.10	0.10	0.10	0.11	0.11	0.13	0.14	0.14	0.14	0.13	0.121
PTC-oil	0.07	0.07	0.07	0.05	0.05	0.07	0.11	0.11	0.11	0.11	0.083
HFC-air	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.06	0.031
HFC-H20	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.06	0.031
HFC-salt	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.06	0.031
PDR	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.014
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Operational and Maintenance Costs

	CPC-fl	LFR	CLFR	CPC	PTC-dsg	PTC-oil	HFC-air	HFC-H20	HFC-salt	PDR	Priority Vector
CPC-fl	0.23	0.23	0.26	0.26	0.24	0.21	0.19	0.19	0.19	0.15	0.216
LFR	0.23	0.23	0.26	0.26	0.24	0.21	0.19	0.19	0.19	0.15	0.216
CLFR	0.12	0.12	0.13	0.13	0.16	0.16	0.15	0.15	0.15	0.13	0.140
CPC	0.12	0.12	0.13	0.13	0.16	0.16	0.15	0.15	0.15	0.13	0.140
PTC-dsg	0.08	0.08	0.06	0.06	0.08	0.11	0.11	0.11	0.11	0.12	0.093
PTC-oil	0.06	0.06	0.04	0.04	0.04	0.05	0.08	0.08	0.08	0.10	0.062
HFC-air	0.05	0.05	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.07	0.039
HFC-H20	0.05	0.05	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.07	0.039
HFC-salt	0.05	0.05	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.07	0.039
PDR	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.015
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Land Usage

	CLFR	PTC-dsg	CPC-fl	LFR	PTC-oil	HFC-air	HFC-H20	HFC-salt	PDR	CPC	Priority Vector
CLFR	0.31	0.36	0.36	0.36	0.36	0.24	0.24	0.24	0.19	0.16	0.283
PTC-dsg	0.10	0.12	0.12	0.12	0.12	0.15	0.15	0.15	0.13	0.13	0.128
CPC-fl	0.10	0.12	0.12	0.12	0.12	0.15	0.15	0.15	0.13	0.13	0.128
LFR	0.10	0.12	0.12	0.12	0.12	0.15	0.15	0.15	0.13	0.13	0.128
PTC-oil	0.10	0.12	0.12	0.12	0.12	0.15	0.15	0.15	0.13	0.13	0.128
HFC-air	0.06	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.08	0.09	0.054
HFC-H20	0.06	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.08	0.09	0.054
HFC-salt	0.06	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.08	0.09	0.054
PDR	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.05	0.027
CPC	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.016
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Tolerance of Slope

	PDR	HFC-air	HFC-H20	HFC-salt	PTC-oil	PTC-dsg	CLFR	LFR	CPC	CPC-fl	Priority Vector
PDR	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.192
HFC-air	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.192
HFC-H20	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.192
HFC-salt	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.192
PTC-oil	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.038
PTC-dsg	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.038
CLFR	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.038
LFR	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.038
CPC	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.038
CPC-fl	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.038
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of Water Usage

	PDR	CPC	HFC-air	HFC-salt	CPC-fl	CLFR	LFR	HFC-H20	PTC-dsg	PTC-oil	Priority Vector
PDR	0.30	0.36	0.33	0.33	0.27	0.27	0.27	0.18	0.18	0.18	0.269
CPC	0.15	0.18	0.22	0.22	0.20	0.20	0.20	0.16	0.16	0.16	0.185
HFC-air	0.10	0.09	0.11	0.11	0.14	0.14	0.14	0.13	0.13	0.13	0.121
HFC-salt	0.10	0.09	0.11	0.11	0.14	0.14	0.14	0.13	0.13	0.13	0.121
CPC-fl	0.07	0.06	0.05	0.05	0.07	0.07	0.07	0.11	0.11	0.11	0.076
CLFR	0.07	0.06	0.05	0.05	0.07	0.07	0.07	0.11	0.11	0.11	0.076
LFR	0.07	0.06	0.05	0.05	0.07	0.07	0.07	0.11	0.11	0.11	0.076
HFC-H20	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.025
PTC-dsg	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.025
PTC-oil	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.025
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of the Suitability to Operate at the Proposed Scale for Southern Spain (100MW)

	PDR	HFC-air	HFC-salt	HFC-H20	PTC-dsg	PTC-oil	CLFR	LFR	CPC-fl	CPC	Priority Vector
PDR	0.18	0.18	0.18	0.18	0.19	0.19	0.18	0.18	0.16	0.13	0.176
HFC-air	0.18	0.18	0.18	0.18	0.19	0.19	0.18	0.18	0.16	0.13	0.176
HFC-salt	0.18	0.18	0.18	0.18	0.19	0.19	0.18	0.18	0.16	0.13	0.176
HFC-H20	0.18	0.18	0.18	0.18	0.19	0.19	0.18	0.18	0.16	0.13	0.176
PTC-dsg	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.10	0.10	0.075
PTC-oil	0.06	0.06	0.06	0.06	0.06	0.06	0.09	0.09	0.10	0.10	0.075
CLFR	0.05	0.05	0.05	0.05	0.03	0.03	0.04	0.04	0.06	0.09	0.049
LFR	0.05	0.05	0.05	0.05	0.03	0.03	0.04	0.04	0.06	0.09	0.049
CPC-fl	0.04	0.04	0.04	0.04	0.02	0.02	0.02	0.02	0.03	0.07	0.034
CPC	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.014
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of the Suitability to Operate at the Proposed Scale for India (1MW)

	CLFR	LFR	CPC-fl	PDR	PTC-dsg	PTC-oil	HFC-air	HFC-salt	HFC-H20	CPC	Priority Vector
CLFR	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.15	0.166
LFR	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.15	0.166
CPC-fl	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.15	0.166
PDR	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.15	0.166
PTC-dsg	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.15	0.166
PTC-oil	0.06	0.06	0.06	0.06	0.06	0.06	0.08	0.08	0.08	0.10	0.068
HFC-air	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.05	0.029
HFC-salt	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.05	0.029
HFC-H20	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.05	0.029
CPC	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.015
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of the Suitability to Operate at the Proposed Scale for California (500MW)

	HFC-air	HFC-salt	HFC-H20	PDR	PTC-dsg	PTC-oil	CLFR	LFR	CPC-fl	CPC	Priority Vector
HFC-air	0.19	0.19	0.19	0.19	0.21	0.21	0.17	0.17	0.16	0.12	0.182
HFC-salt	0.19	0.19	0.19	0.19	0.21	0.21	0.17	0.17	0.16	0.12	0.182
HFC-H20	0.19	0.19	0.19	0.19	0.21	0.21	0.17	0.17	0.16	0.12	0.182
PDR	0.19	0.19	0.19	0.19	0.21	0.21	0.17	0.17	0.16	0.12	0.182
PTC-dsg	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.10	0.11	0.11	0.072
PTC-oil	0.05	0.05	0.05	0.05	0.05	0.05	0.10	0.10	0.11	0.11	0.072
CLFR	0.04	0.04	0.04	0.04	0.02	0.02	0.03	0.03	0.05	0.11	0.042
LFR	0.04	0.04	0.04	0.04	0.02	0.02	0.03	0.03	0.05	0.11	0.042
CPC-fl	0.03	0.03	0.03	0.03	0.01	0.01	0.02	0.02	0.03	0.09	0.031
CPC	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.012
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Pairwise comparison matrix showing preferences for the collectors in terms of the Suitability to Operate at the Proposed Scale for The Sahara Desert (2000MW)

	HFC-air	HFC-salt	HFC-H20	PDR	PTC-dsg	PTC-oil	CLFR	LFR	CPC-fl	CPC	Priority Vector
HFC-air	0.22	0.22	0.22	0.24	0.23	0.23	0.19	0.19	0.17	0.15	0.207
HFC-salt	0.22	0.22	0.22	0.24	0.23	0.23	0.19	0.19	0.17	0.15	0.207
HFC-H20	0.22	0.22	0.22	0.24	0.23	0.23	0.19	0.19	0.17	0.15	0.207
PDR	0.11	0.11	0.11	0.12	0.18	0.18	0.16	0.16	0.15	0.14	0.142
PTC-dsg	0.04	0.04	0.04	0.03	0.05	0.05	0.09	0.09	0.10	0.10	0.064
PTC-oil	0.04	0.04	0.04	0.03	0.05	0.05	0.09	0.09	0.10	0.10	0.064
CLFR	0.04	0.04	0.04	0.02	0.02	0.02	0.03	0.03	0.05	0.07	0.035
LFR	0.04	0.04	0.04	0.02	0.02	0.02	0.03	0.03	0.05	0.07	0.035
CPC-fl	0.03	0.03	0.03	0.02	0.01	0.01	0.02	0.02	0.02	0.05	0.025
CPC	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.015
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

Annex 4: Case Study Scenarios

Southern Spain, California, The Sahara Desert, and Gujarat, have been selected for the implementation of a solar thermal system. Each location’s climate is determined along with their political standings in terms of government legislation that exists to promote renewable projects. The land and local population has also been considered as well as the likely scale for a solar thermal power plant in these areas. Using this information, four suitable case study scenarios have been developed for the AHP analysis.

Southern Spain

Spain’s climate varies greatly from one region to another. Southern Spain, including the eastern coast, has a Mediterranean climate with average temperatures of 11ºC in the winter and 23ºC in the summer. Annual rainfall is between 230mm – 600mm in this region. Temperatures in the past have reached 47°C in Seville, which is home to the world’s largest solar towers PS10 and PS20. Spain also has Europe’s first parabolic trough plant, Andasol 1. Spain ranks as one of the most suitable locations for solar power, receiving more sunshine than any other European country. Spain is also the fourth largest manufacturer of solar power technology worldwide.

Spain was the first country to implement feed-in tariffs for CSP, meaning that the regional or national electricity suppliers have to buy renewable generated electricity at an above-market rate set by the government for a guaranteed 25 year period. Another aspect that was crucial in developing the CSP industry in Spain was the granting of permission for solar plants to use natural gas as a back up to increase their operational capacity factor. The combination of these decrees meant that CSP technology could now compete with conventional power plants. However a limit of 500MW of solar power generation in Spain has been set. Once this capacity is reached, the tariffs will be removed. The current amount of solar thermal generated energy, 183MW, is hoped to rise substantially within the next couple of years.

Southern Spain seems suitable for large scale grid-connected commercial generating power stations providing power to the local populous, which has been proven successfully in Seville. For this case study the following scenario is proposed:

Financing for the initial development has been easy to come by with many enthusiastic investors keen to take advantage of the political incentives while they remain in place. Initial proposals are for a mid to large scale 100MW plant. Conditions for the selected region are seen to be very good, with few extreme weather conditions such as high winds and temperatures below freezing.

California – Mojave Desert

The Mojave Desert occupies a significant area in south-eastern California. The summer season in the Mojave brings with it temperatures as high as 50ºC in some of its basins, as well as other weather extremes such as the North American Monsoon. While the Desert receives less than 250mm of rain a year, windy days are common across the region. While solar collectors can re-orientate to protect themselves, wind is a major factor in damaging CSP systems, particularly the receivers which are expensive as well as the mirrors; around 3000 mirrors are replaced every year at the SEGS plant. Autumn is mainly dry with temperatures between 21 - 32ºC. Winter can see extreme colds of -7ºC on the valley floor and far less in higher elevations. Storms from across the Pacific bring rain and snow but with long gaps between storms, temperature can rise back up to 27ºC. Spring temperatures are often above 38ºC with some storms influencing these temperatures.

The Mojave Desert was once the location for the main developments of solar power pushing the technology forward, but when tax credits and other subsidies were adjusted with a fall in oil prices, expansion plans for the world’s largest solar power station fell through. This caused its developers, Luz Systems, to file for bankruptcy in 1991, which led to concerns for future developments of CSP technologies[20]. Luz Systems financial difficulties can be attributed to the unpredictable nature of the then existing policies, which were based on fossil fuel prices. Fossil fuel prices can be affected globally by many factors, emphasising why guaranteed fixed tariffs are so important [64].

California has now also followed suit aiming to achieve an ambiguous 20% of their electricity sales to be served by renewable energy sources by 2010 and extended to 33% by 2020. To achieve this, a number of financial incentive plans have been put into place, once again starting a renewed enthusiasm in developing large solar power stations in this region. Further detail on all the financial incentive plans can be obtained from the US Department of Energy [65]**.**

The case study scenario for California assumes that the development of a 500MW plant has been initiated. Funding has however been difficult with some investors withdrawing due to fears caused by historical records in this region of further large scale solar thermal developments leading to financial difficulties. While weathers can see extreme temperature highs, designers have also had to consider the problems faced with the below freezing temperatures and the North American monsoon. It has also been suggested that some of the hotter locations on the valley basins could be utilized as large available areas of suitable level land can be difficult to come by.

Gujarat

The weather conditions across the whole of India, as well as Gujarat, are very variable. While coastal regions have a humid, mild climate with moderate amounts of rainfall in the monsoon period, inland areas experience a far more extreme climate. On average summers are very hot and dry, with temperatures reaching as high as 46ºC during the day and 34ºC at night. The winters are still very warm at 29 ºC during daylight and 12 ºC at night. The monsoon season can extend from the middle of June to September with extremely hot humid conditions before its arrival brings temperatures down to 38 ºC.

India has also recently announced feed-in tariffs to the maximum of Rs 15/kWh for grid connected systems in March 2008, and states are now starting to take this up with West Bengal being the first.

Gujarat, as well as numerous other places in India, may well be more suited to smaller off grid CSP systems with a number of smaller communities not being on a large national grid system. For the Indian case study, the following proposals are made:

Indian businesses have collaborated with European investors to develop a local small marketable solar thermal system to power local communities that are away from a grid network, while some states have yet to adopt the relatively new governments plans for feed-in tariffs, these should be utilized were possible. Suggested scales range from 100kW – 1MW. Weather conditions to contend with in India are the monsoon season bringing with it high winds, however freezing temperatures are likely to be infrequent.

Sahara Desert

The Sahara is the world’s largest hot desert at over 9 million kilometres squared. The region’s climate can be categorized into two types; the north, a dry subtropical climate consisting of annually high temperatures with cold winters and hot summers with two rainy seasons, and the south, a dry tropical climate forming dry mild winters, and a hot dry season before the rainy season.

The rainy seasons in the north can cause potential flash flooding, usually around August. The dry tropical climate of the southern region, at high elevations, receives temperatures well below freezing. In the western regions the cold Canary current reduces rainfall and lowers the average temperature, increasing the humidity and the potential of fog.

The Sahara Desert has been linked with plans to establish huge scale solar thermal plants for electricity to be exported to the whole of Europe, and while financing plans have been initiated, it remain dubious to how far the projected plans will go.

With Africa receiving 95% of the world’s best winter sunlight and an abundance of other renewable resources to harness, Africa is well situated to develop the means of providing substantial amounts of energy for its own requirements and exportation. Around 50% of Africa’s electricity is generated by *Eskom* who run mainly coal fired power stations, producing 45% of the country’s greenhouse gases alone, and this is with the majority of South Africa being without power. The reluctance towards renewable energy in Africa can be linked to the lack of political legislation that has been pioneered in other countries. The success seen with feed-in tariffs could promote numerous industries to develop a greater interest in regions such as the Sahara Desert for renewable projects.

With the abundance of land unlike anywhere else, the Sahara stands out as a location with great potential for huge scale CSP systems. In this case study the following hypothesis is made:

African consortiums with large European investors with additional financial backing from the EU have begun plans for a multi-networked solar system totalling over 2000MW. While initial investments have been successful the total amount required for the project could be difficult to come by. Africa’s lack of political incentives in the use and development of renewables has also made the long term payback period a concern for some parties.

Annex 5: Pairwise Comparison of Criteria for Southern Spain, Mojave Desert, Gujarat, and the Sahara Desert

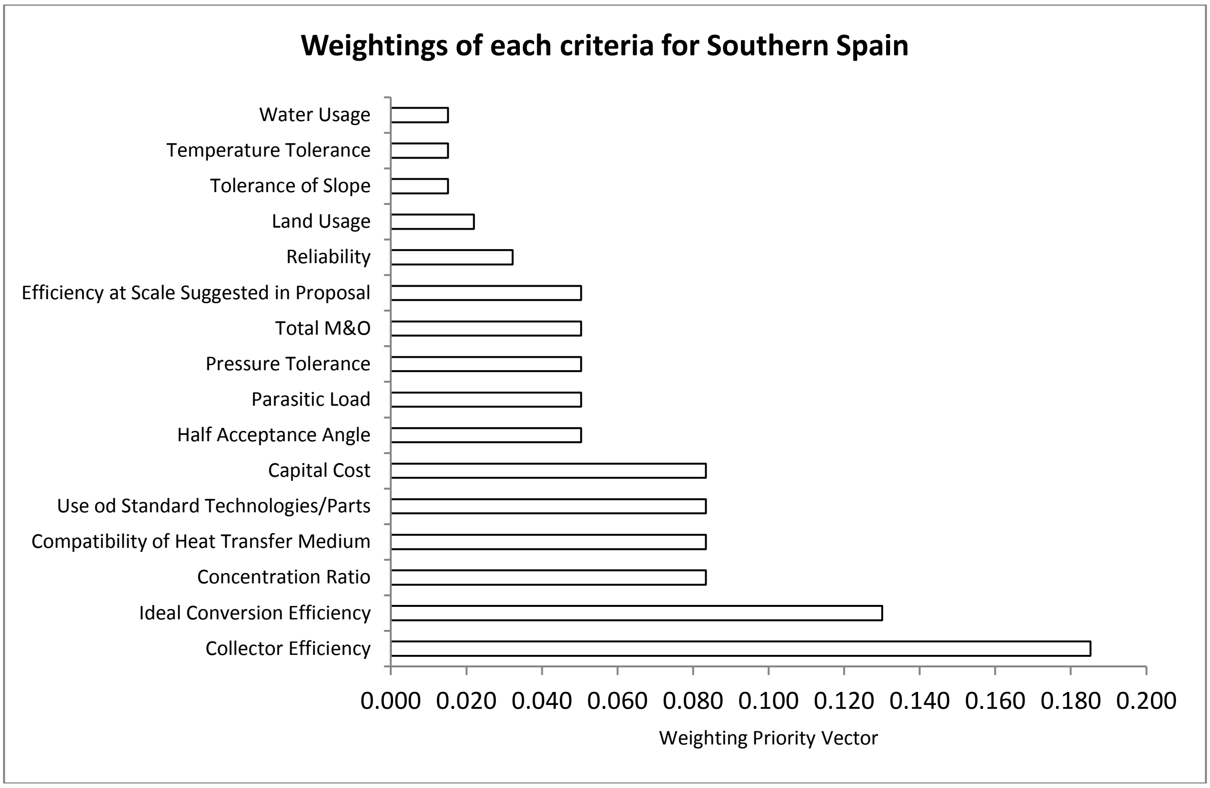


Fig.6 Pairwise comparison matrix for the development of the weighting vectors for Southern Spain.

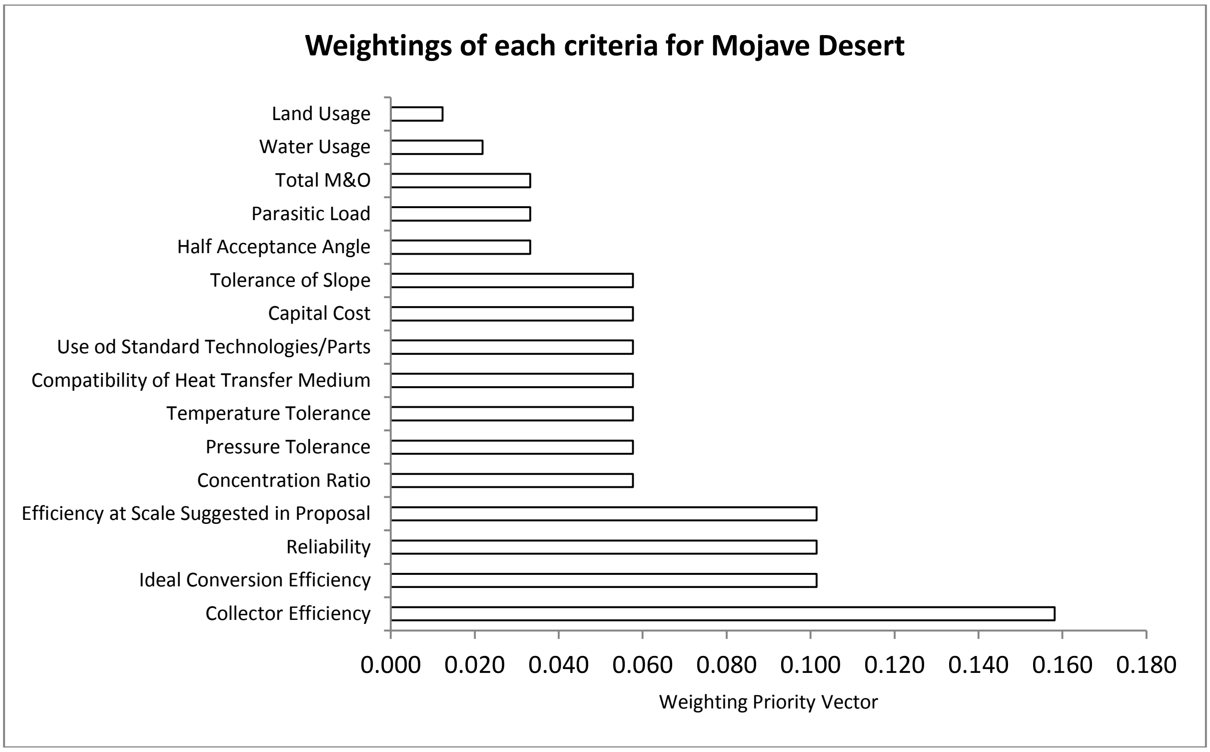


Fig.7 Pairwise comparison matrix for the development of the weighting vectors for the Mojave Desert.

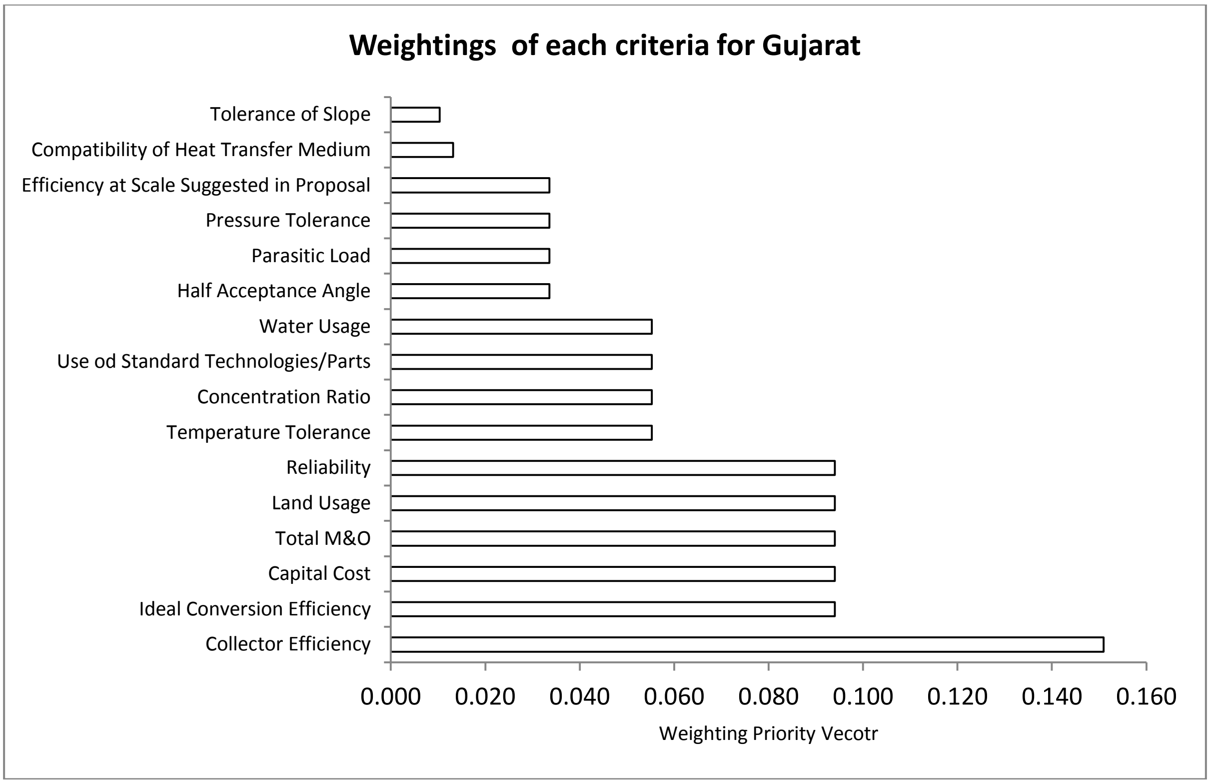


Fig.8 Pairwise comparison matrix for the development of the weighting vectors for Gujarat.

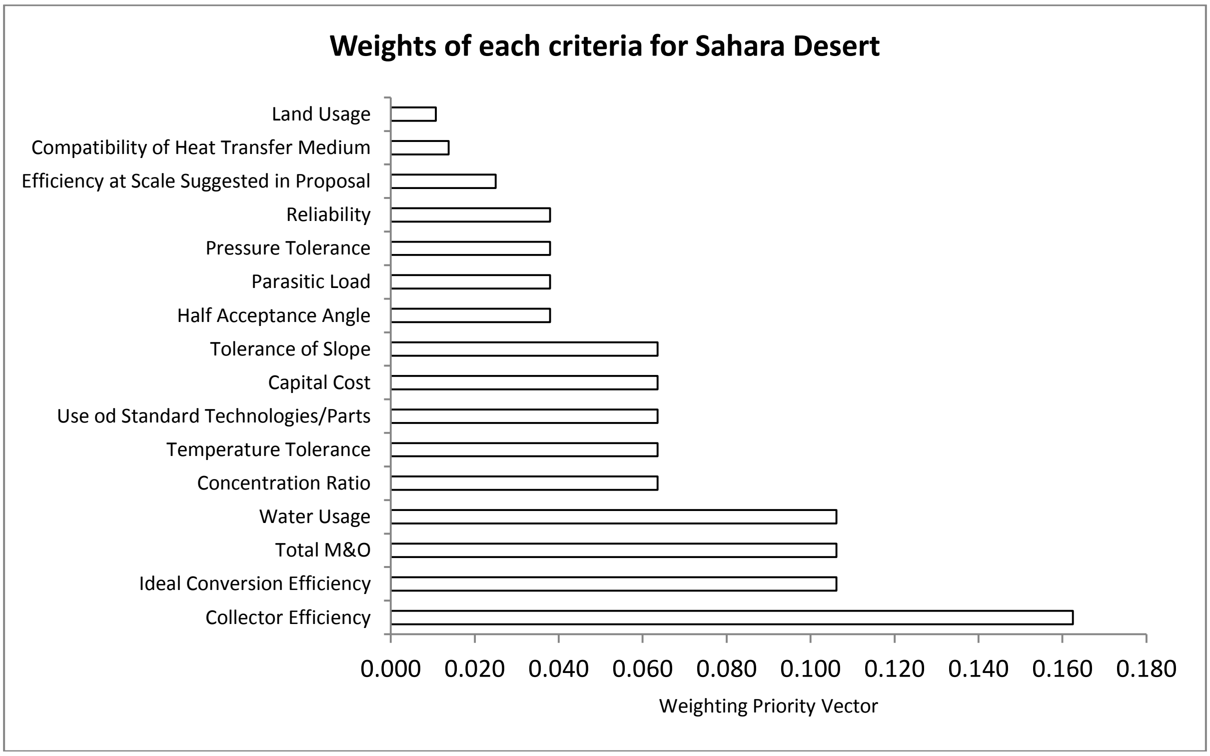


Fig.9 Pairwise comparison matrix for the development of the weighting vectors for the Sahara Desert.

Figure and Table

Fig.1. Flow diagram showing the methodology for technology evaluation and selection based on the AHP.

Fig.2. Decision hierarchy tree for selection of a suitable solar thermal collecotor for Gujarat (a) with the expanded hierarchy tree for the technical criteria (b), environmental criteria (c), and financial criteria (d), showing the technologies ordered on preference for each sub-criterion, using the characteristic values (table.1) from the literature review.

Fig.3. Final results from the AHP study showing each solar thermal collector’s percentage preference for Southern Spain (a), Gujarat (b), Mojave Desert (c) and the Sahara Desert (d).

Fig.4. Sensitivity study for Gujarat showing the potential range of the percentage preference for each alternative.

Table 1. Characteristic values for solar thermal technologies and their alternatives, under the criteria of; technical, financial, and environmental, developed from the literature review.

Annexes

Fig.5. The Decision Hierarchy Tree for the sub criteria, chemical compatibility.

Fig.6. Pairwise comparison matrix for the development of the weighting vectors for Southern Spain.

Fig.7. Pairwise comparison matrix for the development of the weighting vectors for the Mojave Desert.

Fig.8. Pairwise comparison matrix for the development of the weighting vectors for Gujarat.

Fig.9. Pairwise comparison matrix for the development of the weighting vectors for the Sahara Desert.

Table 2.1 Sub criteria selected for the AHP study.

Table 2.2 List of the solar technology alternatives used in the AHP study.

Table 2.3 Pairwise comparison scale values for the level of preference to be used in the pairwise comparison matrix.

Table 2.4 Pairwise comparison matrix showing how preferred each alternative is in terms of their chemical compatibility.

Table 2.5 Priority vectors of each alternative for the chemical compatibility.

Table 2.6 Calculation of λ_{max} for the chemical compatibility sub criteria.

Table 3.1. Full pairwise comparison matrix for the development of the priority vectors.

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