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Utilization of Supplementary Energy Sources for Cooling In Hot Arid Regions via Decision-Making Model

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ABSTRACT

In hot arid regions where long hot summers are common place, energy consumption represents an aspect of particular concern especially as related to peak load. The selection of the best energy option is a complex function of many various variables and thus represents a multi-criteria decision-making problem. This study involved building a decision-making model in order to optimize energy consumption in hot arid regions. The study examined the best possible choice of energy source under hot arid conditions based on a number of aspects (criteria) that were subject to weighting by experts. The energy options considered were limited to commercial electricity, photovoltaic (PV), solar thermal, and the combination (coupling) of electricity and PV. The tool known as Analytical Hierarchy Process (AHP) along with the associate software package EXPERT CHOICETM were used in building the model and drawing conclusions. The findings of the study indicated that under normal prevailing conditions, PV represents the best choice of energy source in hot arid regions. The study demonstrated that the AHP provided a powerful analysis tool and lead to a highly consistent judgment and a quite reliable decision.

***Keywords*: Analytical Hierarchy Process (AHP), Decision support systems; Energy optimization; Hot arid regions; Supplementary energy**

1. INTRODUCTION

Energy is an essential input for sustainable socio-economic development of all nations. Therefore, several new concepts of energy planning and management including energy conservation and efficiency, waste recycling, integrated energy planning, and renewable energy sources have been introduced and adopted. The introduction of energy efficiency measures and renewable energy concepts were, in many cases, encouraged by newly-established governmental policies (Belgina et al., 2008; Abulfotuh, 2007).[1]

In hot arid regions, long and extended warm and dry summers, low rates of rain and humidity, lack of green cover, and the large temperature fluctuations between day and night make sort of standard descriptions. In such regions, the ventilating and air-conditioning (VAC) installations, that are typically the most energy-intensive among energy-consuming activities, are essential for securing healthy, safe and suitable indoor thermal conditions for building occupants and stored materials.

Throughout the Arabian Peninsula which is a predominantly hot arid region and in similar regions in other parts of the world, space cooling, a primary driver of energy consumption, is of paramount importance since the power used for the air-conditioning of buildings in some countries accounts for 70% of the electrical power production (Al-Temeemia and Harris, 2004)[2]. In Saudi Arabia, where energy demand has been growing at alarming rates (Qader, 2009[3]; Al-Ajlana et al., 2006; Alnatheer, 2005[4]), many researchers examined the potential of utilizing renewable energy sources. The majority of such studies considered most notably solar energy as a promising potential supplementary energy source due to its high availability and irradiation rates (Shaahid and El-Amin, 2009[5]; Rehman and Al-Hadhrami, 2010[6]). In Kuwait, domestic air-conditioning operates from the beginning of April to the end of October. In this sector, buildings account for about 75% to 80% of the total electric power consumption, mainly due to the impact of air-conditioning (Al-Ajmia, Loveday, and Hanby, 2006)[7].

In such regions, the association of peak cooling demand in summer with high solar energy availability offers a window of hope to exploit solar energy for cooling in a more efficient, integrated and comprehensive manner.

Researchers and scientists made early attempts for developing integrated energy models that link both commercial and renewable energy sources. An early simple model had been proposed that made it possible to find conditions for the economic viability of solar thermal or photovoltaic energy utilization (Landsberg, 1977)[8]. The research in this direction attempts to match solar thermal technologies with thermally driven cooling equipment like absorption, adsorption and desiccant chillers (Argiriou, 2005)[9]. A comprehensive review of these technologies is given in several references (Srikhirin, Aphornratana, and Chungpaibulpatana, 2001[10]; Dieng and Wang, 2001[11]; Floridesa, 2002[12]; Grossman, 2002[13]; Henning, 2004[14]).

The high energy consumption in cooling and other energy-consuming systems in hot arid regions due to the climatic specifications make implementing and selecting among the various possible renewable energy sources and forms for energy production a multi-criteria decision-making (MCDM) problem. The rational decision-making in energy supply system options, planning, management and economy is helpful to the sustainable development. However, the complex interactions of energy systems make decision-making more difficult. Sustainable and renewable energy decision-making using multi-criteria decision analysis (MCDA) provides a method to eliminate the difficulty and has attracted the attention of decision makers for a long time.

This work introduces a decision support model utilizing the Analytical Hierarchy Process (AHP). The intention is to help decision makers implement a suitable type of renewable energy, limited in this study to solar (thermal and photovoltaic forms) along with the widely used commercial electric power, in hot arid regions to optimize energy use and attempt to trim the associated and in many cases prohibitive costs.

2. MATERIALS AND METHODS

2.1 The analytical hierarchy process (AHP)

AHP is a widely used multi-criteria decision making tool designed to solve MCDM problems. The AHP method in a rank order weighing method is gaining popularity because of its understandability and application simplicity. In addition to energy systems, the AHP has found wide utility in several domains like biomedical and industrial applications (Dweiri and AL-Oqla, 2006[15]; AL-Oqla and Hayajneh, 2007[15]) as well as social, economic, agricultural, ecological and biological systems (Chatzimouratidis and Pilavachi, 2009[16]; Buchholz et al., 2009[17]).

Unlike conventional methods, AHP uses pair-wise comparisons which allow verbal judgments that enhance the precision of findings, and further allow accurate ratio and scale priorities. AHP helps capture both subjective and objective evaluation measures, providing a useful mechanism for checking the consistency of the evaluation and alternatives, thereby, reducing bias in decision making (AL-Oqla and Hayajneh, 2007[15]). When making complex decisions involving multiple criteria, the first step is to decompose the main goal into its constituent sub-goals, also called objectives, progressing from the general to the specific. In its simplest form, this structure comprises a goal, criteria or objectives and alternative level. Each set of criteria would then be further divided, realizing, however, that the more criteria included, the less important each individual criterion may become. Fig. 1 illustrates the typical basic structure.

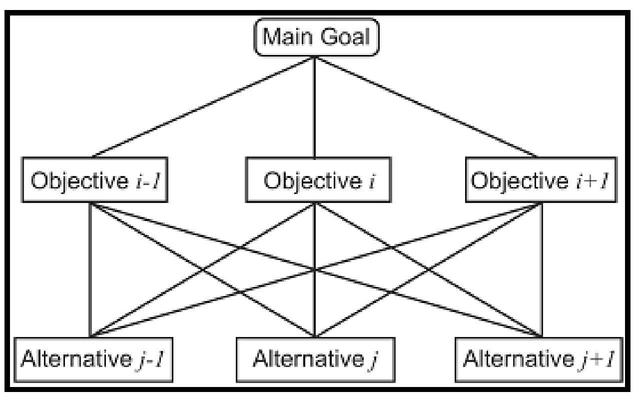

Figure 1. AHP hierarchy of goals, objectives and alternatives.

In the typical hierarchical structure, the main goal is laid on the top while the decision alternatives are at the bottom. Between the goal and alternatives reside the attributes of the decision problem such as the selection criteria and objectives. Next, relative weights to each item in the corresponding level are assigned. Each criterion has a local (immediate), and global priority. The latter shows the relative importance of alternatives. The sum of all the criteria beneath a given parent criterion in each layer must be unity. After the criteria factors are identified, each level is given a score with respect to its parent using a relative relational basis by comparing one choice to another. Relative scores for each choice are computed within each leaf of the hierarchy. Scores are then synthesized through the model, yielding a composite score for each choice at every layer, as well as an overall score. This relative scoring within each level will result in a matrix of scores, say *a(i, j)*. The matrix holds the expert judgment of the pair-wise comparisons.

As the judgment should be consistent, inconsistency test is required to validate the expert knowledge. In general, the inconsistency ratio should be less than 0.1 or so to be considered reasonably consistent (AL- Oqla and Hayajneh, 2007[15]). Particularly, a matrix $a\,(i, j)$ is said to be consistent if all its elements follow the transitivity and reciprocity rules below:

$$a_{i,j} = a_{i,k} \cdot a_{k,j} \tag{2.1.1}$$

$$a_{i,j} = {}^{1}\!/_{a_{j,i}} \tag{2.1.2}$$

where i, j, and k are any alternatives of the matrix (Ishizaka and Lusti, 2003[18]). The relational scale used in ranking is presented in Table 1.

The pair-wise comparison matrices can also be represented as

$$A = \begin{bmatrix} a_{11} & \Lambda & a_{1n} \\ \mathrm{M} & \mathrm{M} & \mathrm{M} \\ a_{n1} & \Lambda & a_{nn} \end{bmatrix} = \begin{bmatrix} w_1/w_1 & \Lambda & w_1/w_n \\ \mathrm{M} & \mathrm{M} & \mathrm{M} \\ w_n/w_1 & \Lambda & w_n/w_n \end{bmatrix} \tag{2.1.3}$$

For a consistent matrix, we can demonstrate that

$$A = \begin{bmatrix} w_1/w_1 & \Lambda & w_1/w_n \\ \mathrm{M} & \mathrm{M} & \mathrm{M} \\ w_n/w_1 & \Lambda & w_n/w_n \end{bmatrix} \times \begin{bmatrix} w_1 \\ \mathrm{M} \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ \mathrm{M} \\ w_n \end{bmatrix} \tag{2.1.4}$$

Table 1. The AHP importance scale.

pair of objectives *i*, *j*:

Relative importance
ves *i* and *j* are of equal importance.
ve *i* is weakly more important than *j*.
ve *i* is strongly more important than *j*.
ve *i* is very strongly more important than *j*.
ve *i* is absolutely more important than *j*.

, 4, 6, 8 are intermediate values.

Or, in matrix form $A.w = nw$ where A is the comparison matrix, w is the eigenvector and n is the dimension of the matrix. The equation above can be treated as an eigenvalue problem.

A detailed presentation of the AHP method, its specific steps, and procedure are found in (Saaty, 1980)[19].

2.2 The AHP model for this study

In this work, several factors and sub-factors affecting the decision making process model to optimize energy use for space cooling in hot arid regions by utilizing solar energy, both thermal and photovoltaic, have been carefully proposed. The list of these criteria is presented in Table 2 that include the dominant four main aspects indicated (Wong and Li, 2008)[20]. These factors (criteria) and their sub-criteria were introduced in the AHP model for this study after wide literature review (Bilgena et al., 2009; Abulfotuh, 2007; Rehman and Al-Hadhrami, 2010; Al-Ajmia, Loveday, and Hanby, 2006).

Then, data collection aimed at evaluating the comparability of the selected criteria was achieved by means of a questionnaire that was sent out to some twenty carefully selected experts in AHP and/or energy worldwide, most of whom are from academic institutions and a few professionals. In fact, eleven respondents returned their filled questionnaires, which was deemed suitable sample for our purposes and this kind of study (Wong and Li, 2008[21]). Fig. 2 shows the AHP model with these factors (criteria) included.

A set of matrices representing pair-wise comparisons were developed for all the levels of the hierarchy. An element in the higher level is assumed to be the governing element for those in the lower level of the hierarchy. The elements in the lower level are compared with respect to one another according to their effect on the governing element above. This yields a square matrix of judgments.

The pair-wise comparison is performed on the basis of how an element dominates the other and the judgments are entered using Saaty's 1 to 9 scale (Saaty, 1980[19]). An element compared with itself is always assigned the value of 1, so the main diagonal entries of the pair-wise comparison matrix are all unity. The expert begins by comparing pairs of main criteria (factors) with respect to the main goal by assigning importance. The number of resulting comparisons is given by $n(n-1)/2$, where n is the dimension of the pair-wise comparison matrix.

Table 2. Factors and sub-factors affecting the decision making process model to the problem addressed in this work.

Main factor	Sub-factor
Economical Impact	• Initial investment cost • Maintenance cost • Operational cost • Payback period • Manufacturing cost
Environmental Impact	• Space requirement • Pollutant emissions • Reliability • Safety • Solid waste byproduct
Social Impact	• Job creation • Promotion of economical development • Noise and visual discomfort • Market maturity • Tourism • Culture and education
Technical Maturity	• Technical know-how • Existence of suppliers of the technology • Consistence of installation and maintenance • Availability • Technology transfer • Availability of local raw materials

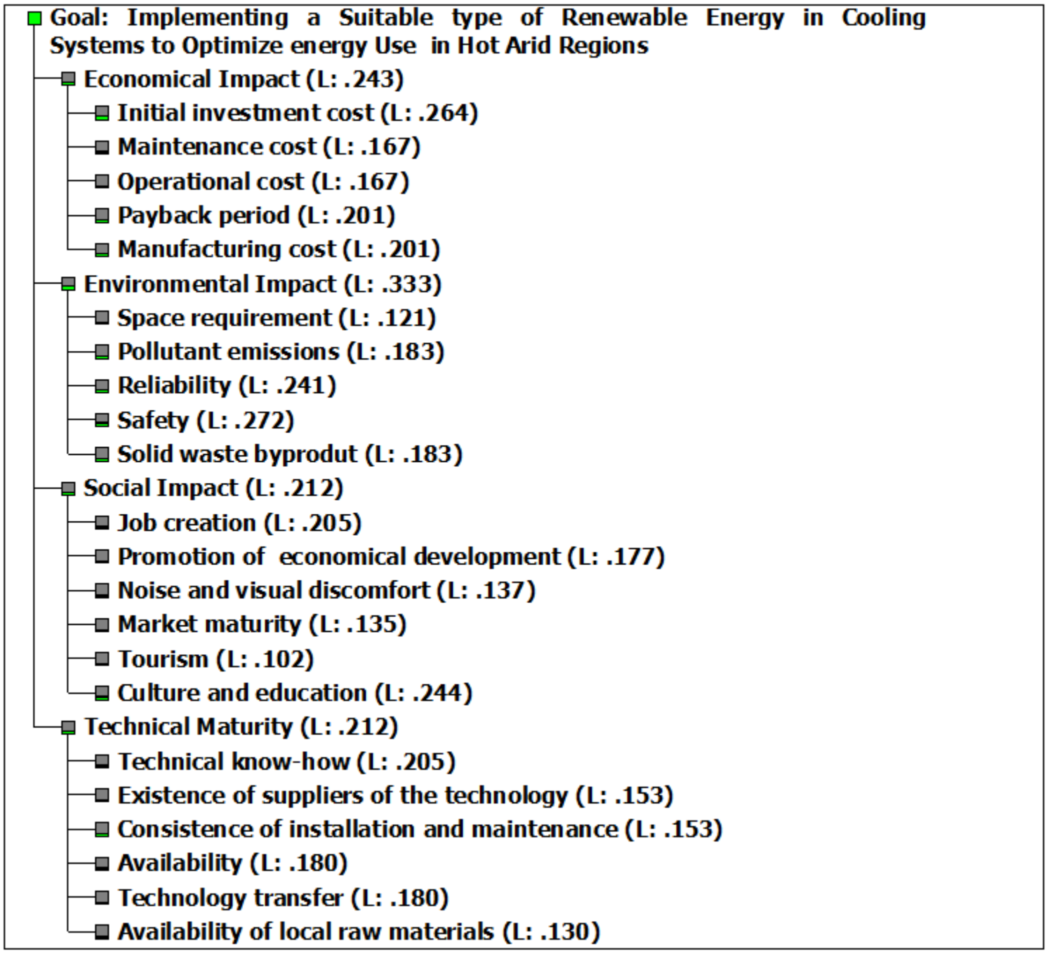

Figure 2. AHP implementation of renewable energy in cooling system hierarchy.

3. RESULTS AND DISCUSSION

Fig. 3 shows the inconsistency as calculated from Eqs. (1) and (2). The figure indicates that model inconsistency is zero, i.e., less than 0.1, meaning that the expert was consistent in his/her judgment.

Fig. 4 represents sort of a summary for the whole model from which the contributions of each main criterion to the model as well as the contributions of each sub-criterion to the main criterion can be read. Specifically, Fig. 4 shows that the environmental impact contributes the most to the goal with a weight of 33.3% while both Social Impact and Technical Maturity contribute the lowest with an equal weight of 21.2 % each. In light of the substantial global environmental deterioration and associated detrimental consequences, this reflects, on the one hand, the significance of the environmental cause in the experts' views and, on the other hand, the strong link between renewable energy technologies and the environmental cause. In addition, the fact that none of the main factors dominates the model (by having a weight 50% or more) indicates a significant level of difficulty in making a decision regarding this issue and thus justifies conducting this work.

	Economica	Environme	Social Impa	Technical M
Economical Impact		(1.5)	1.2	1.2
Environmental Impact			1.5	1.5
Social Impact				1.0
Technical Maturity	Incon: 0.00			

Figure 3. Pair-wise comparisons of the main criteria with respect to the goal in a matrix format as a result of using Expert Choice™ Software.

Fig. 4 also shows that the best choice of supplemental energy source for the application as expressed in the title of this study considered in this study is the photovoltaic (PV) with a weight of 30.6 % taking into consideration the main factors and sub-factors. The second choice is commercial electricity, which is the current widely used energy source, with a weight of 27.0 %. Consequently, the third choice should be the combination between the photovoltaic conversion and electricity with a weight of 22.8%, whereas the last choice is solar thermal with a weight of only 19.8%. It may be noted here that having PV as the first choice while the solar thermal occupies the last rank is consistent with the facts related to solar energy technology. That is, while it is established that PV technology is the best choice for direct electricity production and is considered by many as one of the most promising energy sources for the future, solar thermal in contrast is not as appropriate especially for small-scale applications. Utilizing the data of Fig. 4, a more detailed and useful presentation of findings can be made for the contributions of the sub-criteria to their respective main criterion.

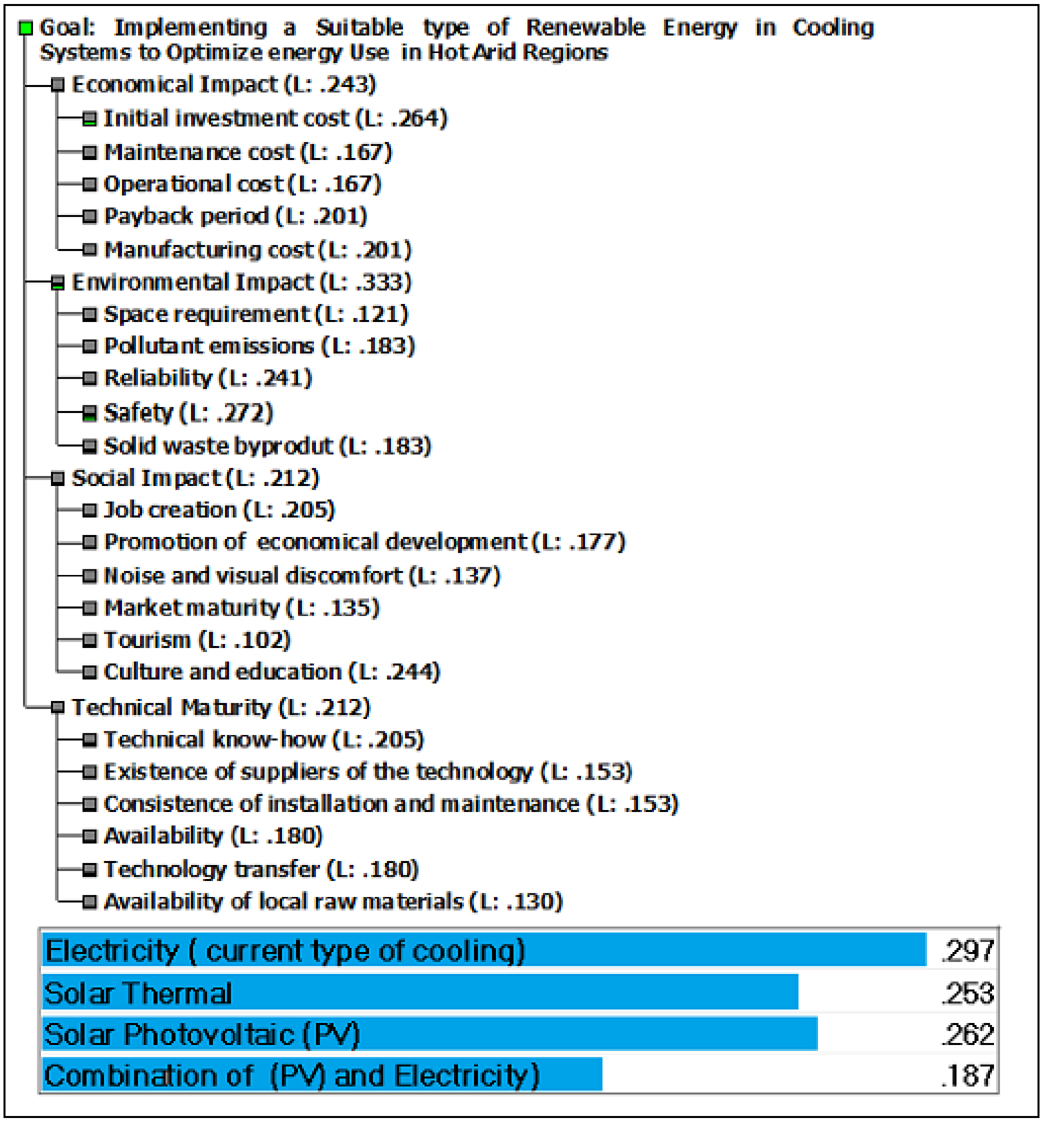

Figure 4. The importance (weight) of the main criterion with respect to the goal and the weight of the sub-criteria with respect to the main criterion.

Fig. 5 presents an example of such a presentation for the Social Impact criterion showing that the Culture and Education contributes 24.4%, Job Creation contributes 20.5%, Promotion of Economical Development contributes 17.7%, Noise and Visual Discomfort contributes 13.7 %, while Market Maturity and Tourism contribute 13.5 % and 10.2 %, respectively. Moreover, data presentation in the format introduced in Fig. 5 demonstrates that the contribution of the sub-criteria to the main Social Impact criterion has an inconsistency of zero indicating again the credibility of expert judgments. Moreover, Fig. 5 presents data in the more convenient graphical format in addition to enabling the analysis of a given main criterion with its sub-criteria. In a similar manner, figures like Fig. 5 can be sketched for the rest of the main criteria. In fact, it turned out that the inconsistency for the contributions of each set of sub-criteria to their respective main criterion was also zero in all cases.

The sensitivity graph of the main factors with respect to the goal is illustrated in Fig. 6. It not only demonstrates that the solar photovoltaic is the best choice for utilizing the energy use for space cooling in hot arid regions, but also shows how sensitive the decision is. A close examination of Fig. 6 reveals that the two competing alternatives, namely, PV and Electricity, are more or less quite close in their sensitivity to the two main criteria of Technical Maturity and Environmental Impact. However, Fig. 6 also shows that PV is strongly positively sensitive and the Electricity is strongly negatively sensitive to the Social Impact, meaning that any reasonable change in the weight of Social Impact will dramatically widen the gap for the benefit of PV as the best choice.

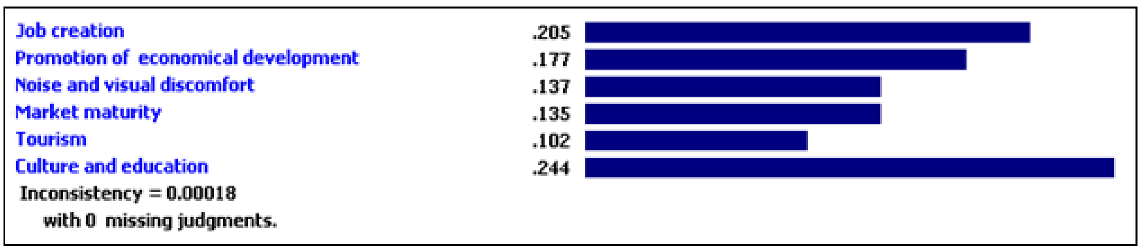

Figure 5. The contribution of sub-criteria to the main criterion (Social Impact).

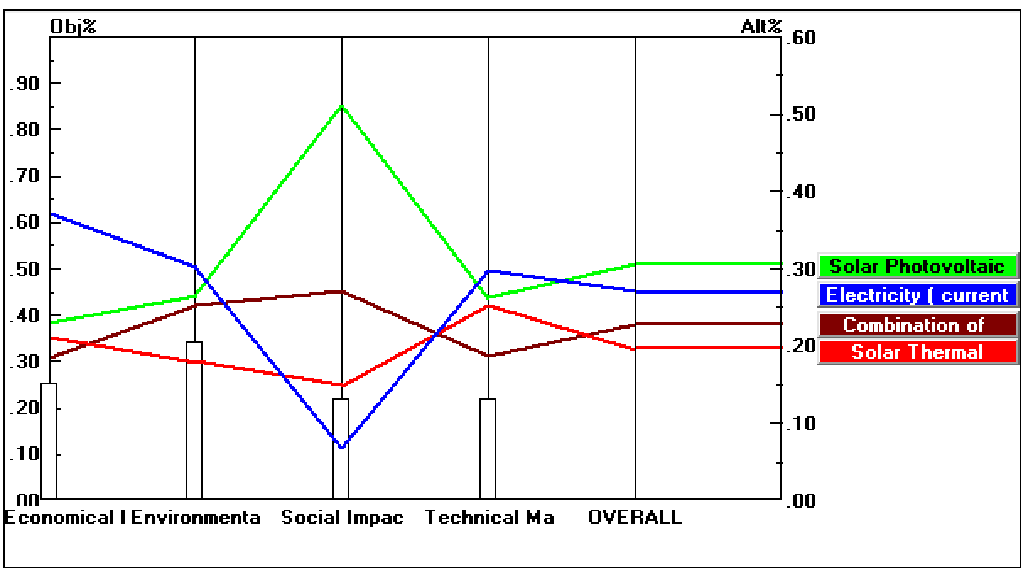

Figure 6. The sensitivity graph of the main factors with respect to the goal.

As such, the governing criterion left is the Economical Impact, which, as Fig. 7 shows, has been almost doubled, which represents an unreasonable change under normal conditions, and thus dominated the model. Fig. 7 still indicates that PV still the best choice even if any of the Environmental Impact, Social Impact and Technical Maturity factors takes a weight of more than expected (i.e; be dominant of the model) as can be clearly seen from Fig. 7. It is noteworthy here also that all indicators show that the future economic advantage is shifting towards the PV technology compared to commercial electricity which further enhances the status of PV as a better energy source and this decision was insensitive to the unexpected change of weights of the studied factors .

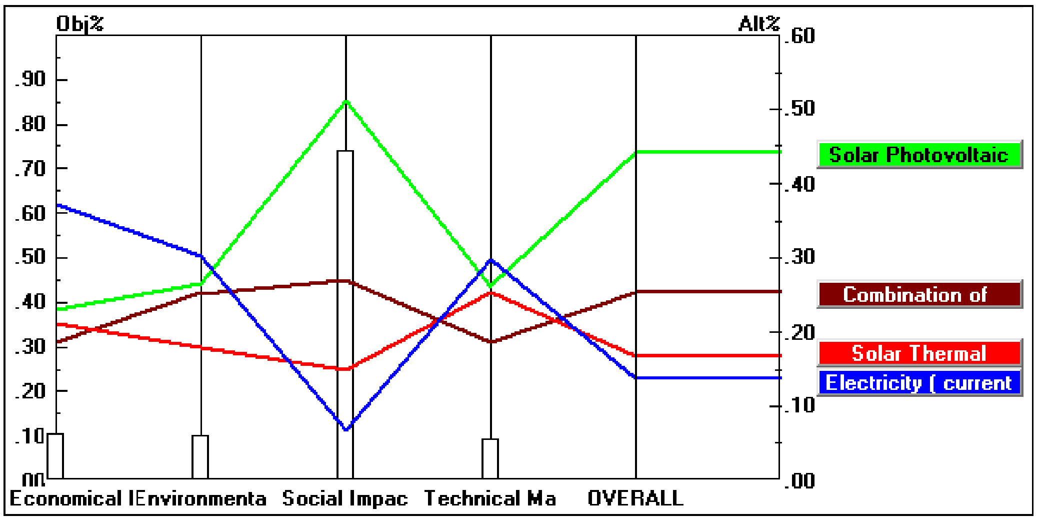

Figure 7. The sensitivity graph of the main factors with respect to the goal if the social impact was given a higher importance.

Overall, these results indicate that having PV as the best choice is undoubtedly quite reliable and is almost insensitive to reasonable changes in the main criteria as introduced in this study based on the model introduced here.

4. CONCLUSION

The selection of an energy source or a combination thereof in hot arid regions that have special features is a function of various variables and thus is a multi-criteria decision making problem. The utilization of the Analytical Hierarchy Process provides a powerful tool for analyzing such problems and results in decision-support models that are quite reliable. The study showed that expert judgments for this study were quite consistent and further indicated that under prevailing conditions, relevant factors and aspects, and energy options (solar and electricity) considered in this study, the PV technology ranks highest as the best choice of energy sources followed by combining commercial electricity and PV. The study demonstrated that these results are highly reliable under reasonable changes in all factors and sub-factors included.

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