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Assessment of Solar Photovoltaic Technologies Using Multiple Perspectives and Hierarchical Decision Modeling: Manufacturers Worldview

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Abstract--**The assessment of photovoltaic technologies using multiple perspectives such as social, technological, economic, environmental, and political (STEEP) have become increasingly important in the last several years. Each perspective is composed of multiple criteria with the social and political perspectives gaining more significance. A hierarchical decision model using expert judgment quantification was developed to provide the relative ranking of the criteria. Such modeling is effective in assessing technologies considering multiple competing perspectives and criteria. The model was operationalized via desirability functions for each criterion. The combined results provide scores for each technology and indicate in which criteria the technology needs improvement. In earlier research the electric utility worldview was considered to assess multiple photovoltaic technologies. In this paper the solar photovoltaic manufacturer worldview case study is presented.**

I. INTRODUCTION

There is a plethora of solar photovoltaic (PV) technologies due to global efforts in research and development (R&D) in renewable energy technologies [1], [2], [3]. Decision makers now need to evaluate technologies taking into account a wide range of perspectives and criteria. Comprehensive methods are needed for today's complex decisions on renewable energy technologies especially since the effect of the decisions will be long lasting and could continue for multiple decades. The conventional methods of assessing technologies using technical performance and economic feasibility still have significant merit; however these have to be supplemented with environmental, social, and political perspectives due the importance of regulatory policies and public sentiment.

II. MULTIPLE PERSPECTIVES AND HIERARCHICAL DECISION MODELING

The basic concepts of decision making and evaluating technologies using multiple perspectives introduced by Harold Linstone can be extended to renewable energy technologies, systems, and processes [4]–[7].

In today's demanding environment multiple perspectives and criteria such as economic feasibility, government regulations, national energy security, and negative environmental impact of energy sources have become even more important in such decisions. Hence, energy generation requirements and decisions must now take into account multiple perspectives and their impacts. This becomes a complex problem. One well established method is to formulate this as an analytical hierarchical decision model (HDM) [8]. With HDM multiple perspectives can be prioritized and their associated criteria can be ranked. Then the following question can be addressed: "In the judgment of the decision makers and experts which perspective or criteria are more important than others?" In particular, which perspectives and criteria have more relative importance for the assessment of solar photovoltaic renewable energy technologies?

Research in this area was initiated by the Research Institute for Sustainable Energy (RISE), Department of Engineering and Technology Management, Portland State University, Oregon. The program was founded by Dundar Kocaoglu and Tugrul Daim of the same department and focuses on assessment of energy technologies and applications under the five perspectives stated above: social, technical, economic, environmental, and political (STEEP).

In this paper, the multiple STEEP perspectives apply to renewable energy and specifically solar photovoltaic energy. These STEEP perspectives consist of multiple criteria and each criteria in-turn may be comprised of multiple sub-criteria (and may be referred to as "factors" for easy distinction). If there are no factors then criteria and factors are the same. The perspective based-criteria can be described as stated below [8]:

- ***Social Perspective.*** This perspective includes criteria or factors that have a significant positive or negative impact on society.
- ***Technological or Technical Perspective.*** This perspective includes criteria or factors that indicate technical performance.
- ***Economic Perspective.*** This perspective includes criteria or factors that are related to economic feasibility and are indicated by cost of technology diffusion, market adoption, and life-cycle costs.
- ***Environmental Perspective.*** This perspective includes criteria or factors that impact environmental sustainability and the earth's natural ecosystems
- ***Political Perspective.*** This perspective includes criteria or factors such as policies, regulations, market special interests, compliance, energy security, national priorities, and government incentives.

In his Ph.D. dissertation, Nasir J. Sheikh describes the criteria that make up the five perspectives to assess solar PV technologies [9]. The criteria were confirmed by experts in their respective perspectives. For example, solar PV technologists confirmed the validity of the technical criteria. These criteria are represented as a hierarchical model and shown below in Figure 1.

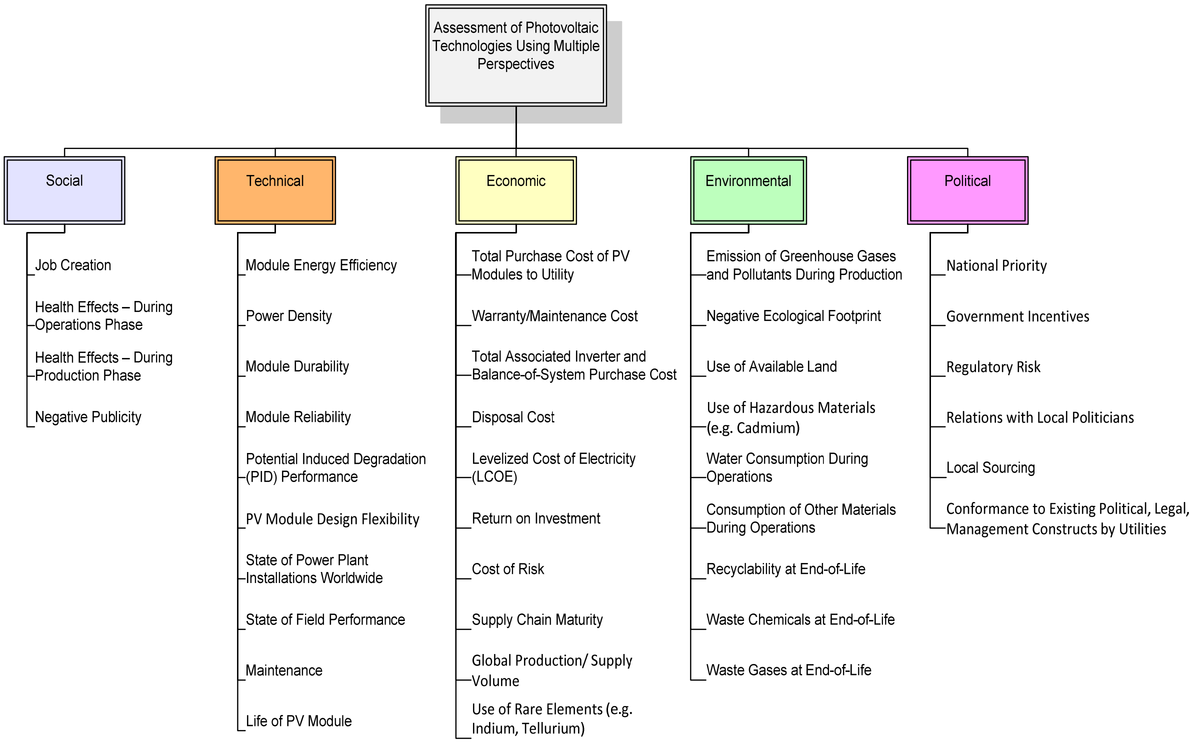

Figure 1: Hierarchical Decision Model with 39 Criteria and No Factors [9]

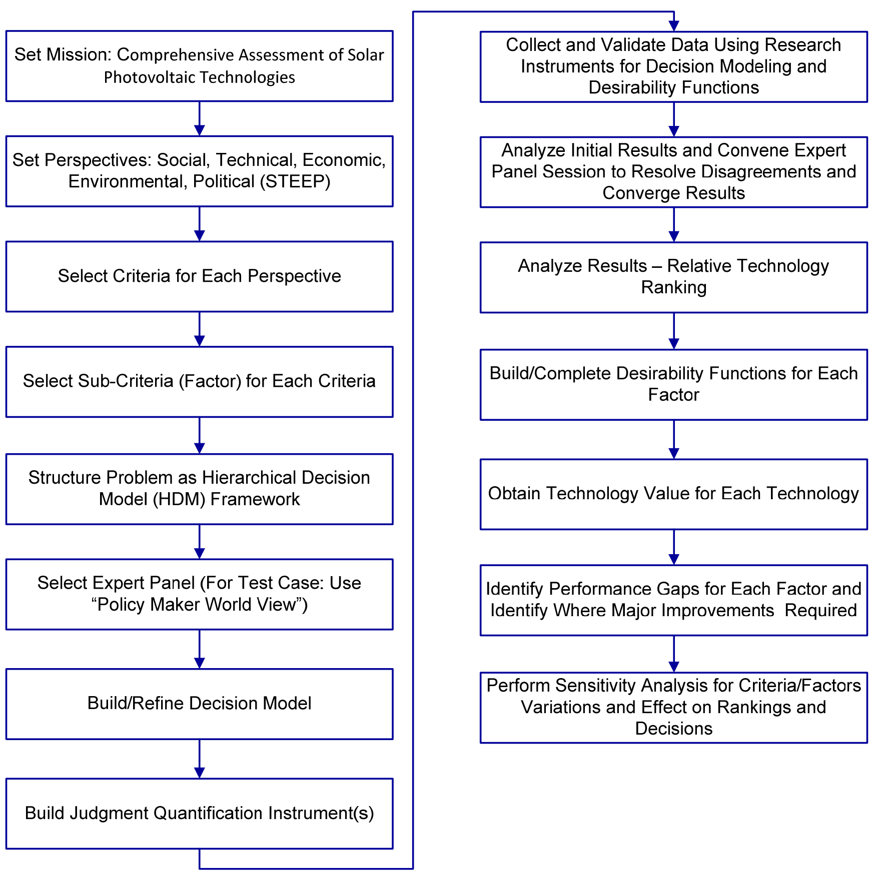

Figure 2: Decision Modeling Process [9]

The decision modeling process for assessing PV technologies has been described in detail earlier and the summary is reproduced in Figure 2 for the reader [9].

A major part of the modeling process is the selection of panels of experts and obtaining their expert judgments. Studies indicate that a panel of ten to fifteen experts per perspective can provide representative and balanced results [10]. In this regard, the experts are similar to experts in the Delphi method. An appropriate expert is defined in the literature as someone who has multiple years of relevant knowledge and experience. He or she has credible opinions and judgments and is respected by his or her peers in the relevant domain of expertise [11], [12], [13].

The expert panels aid the construction and validation of the decision model. The panels are then provided a judgment quantification instrument (which is a research questionnaire) in order to obtain the judgments of the experts. Each question is essentially a pair-wise comparison between criteria. The received data is then analyzed for a respondent's internal inconsistency and disagreement between respondents. These are control measures to ensure judgment data validity and allow for the resolution of any disagreement points. A software tool developed by the Department of Engineering and Technology Management at Portland State University was used to enter research data and derive the initial results. The experts also help construct the desirability functions for each criterion. The desirability functions are a means to provide numerical desirability values for the diverse quantitative and qualitative criteria measures pertaining to the PV technologies under consideration. For a detailed explanation of the desirability functions and values, the reader is referred to the Ph.D. dissertation by Nasir J. Sheikh [9].

However, an equally important aspect is the selection of decision makers to prioritize and rank the perspectives so that the appropriate worldview is represented. The definition of "worldview" is derived from the German word, "Weltanschauung", which means "a comprehensive conception or apprehension of the world especially from a specific standpoint". Hence, a worldview indicates the overall perspective from which one sees and interprets the world. In scholarly literature worldview is defined from an anthropological basis as:

> "Worldview refers to the culturally-dependent, generally subconscious, fundamental organization of the mind. This organization manifests itself as a set of presuppositions or assumptions, which predispose one to feel, think, and act in predictable patterns..."[14].

The above definition is derived from the seminal research by the anthropologist, Michael Kearney [15].

In this paper, a decision maker's worldview simply refers to the frame of reference with respect to the five STEEP perspectives and how they will be prioritized and ranked.

III. ASSESSMENT OF PHOTOVOLTAIC TECHNOLOGIES UNDER DIFFERENT WORLDVIEWS

The decision makers can have different worldviews or philosophical frames of reference which can influence the overall decision. The HDM approach is beneficial in the assessment of PV technologies from diverse worldviews such as: (1) the worldview of electric or power utilities, (2) the worldview of solar photovoltaic module manufacturers, (3) the worldview of national or regional solar policy makers, (4) the worldview of research institutes, and (5) the worldview of research universities and academia.

In earlier research, a case study was completed for an electric utility worldview [9]. The results applied to a Northwest United Stated (US) electric utility. In this paper, research is focused on obtaining results for the solar PV module manufacturers; specifically, the South Korean PV module manufacturers. In parallel, research is underway for a national policy maker worldview. Future research will include a comparative review of the results from different worldviews.

IV. ASSESSMENT OF PHOTOVOLTAIC TECHNOLOGIES: KOREAN PV MANUFACTURERS WORLDVIEW

For this worldview, six representative decision makers were provided research questionnaires to determine ranking of the STEEP perspectives according to their judgments. (The research questionnaire is referred to as the "Judgment Quantification Instrument" and is shown in the Appendix.) The decision makers were asked to evaluate the relative priorities of the five perspectives in fulfilling the mission of PV technology assessment. All the decision makers had Ph.D. degrees in engineering and had between ten to twenty year of experience in the Korean solar PV industry in varying and progressive roles. Although, they represented Korean manufacturers, most had significant exposure and involvement in supplying solar equipment to regions worldwide. Listed below is a summary of their backgrounds:

- Decision Maker-1: Expertise in PV R&D in the solar industry and a government research institute.
- Decision Maker-2: Expertise in the development and commercialization of dye sensitized cell (DSC) PV technology.
- Decision Maker-3: Expertise in the development and commercialization of organic PV (OPV) technology.
- Decision Maker-4: Expertise in the development and commercialization of copper indium gallium (di)selenide (CIGS) PV technology.
- Decision Maker-5: Expertise in the development and commercialization of crystalline silicone (c-Si) PV technology.
- Decision Maker-6: Expertise in PV R&D in a government research institute.

The ranking of the criteria for the STEEP perspectives, the PV technologies to be assessed, and desirability values are unchanged from earlier research [9].

V. RANKING OF STEEP PERSPECTIVES

Considering the case of the Korean solar module manufacturers, the results from the six decision maker representatives were obtained. These included: the arithmetic mean of the relative priority of the perspectives to the mission, the levels of inconsistency, and the level disagreement. The arithmetic mean is used to represent the relative ranking of the perspectives. The results are shown in Table 1. The table also indicates that the decision makers' group judgment quantification is accepted due to their agreement at least at an alpha (α) level of 0.05 [16]. This implies that we can reject the null hypothesis with a confidence level of 95%. Rejecting the null hypothesis also implies that that there is agreement amongst the experts. This is shown by the f-value of 6.2 which is greater than the f-critical value of 2.87 at an α-level of 0.05. An α-level of 0.05 is acceptable in most studies. In fact, in this case we can even reject the null hypothesis at α-level of 0.01 which implies a higher confidence level of 99%. This is because the f-value of 6.2 is still greater than the f-critical value of 4.43 at an α-level of 0.01.

It is evident from the results that the decision makers viewed the economic perspective as the most important followed by the technical perspective. However, the environmental and technical perspectives were comparable. For the assessment of PV technologies the social perspective was considered the least important. However, all five perspectives had over 10% (0.1) contribution to the mission, implying that they were all significant and could not be ignored. The relative rankings of the perspectives are shown in Table 2 below as a ratio with respect to the best perspective. For comparison, the relative rankings of the perspectives from earlier research with the Northwest US Electric Utility Worldview are also shown in Table 3 [9]. Both worldviews considered the economic perspective as the most important followed by the technical and environmental perspectives. However, the relative importance of the political and social perspectives was switched. It should also be noted that in the case of the Korean PV Manufacturers Worldview, the environmental perspective carried more weight than for the Northwest US Electric Utility Worldview.

Table 1: Relative Ranking of Perspectives in Fulfilling the Mission

Assessment of PV Technologies from Korean PV Manufacturers Worldview (PMWV)	Social Perspective	Technical Perspective	Economic Perspective	Environmental Perspective	Political Perspective	Inconsistency
DM1-PMWV	0.16	0.22	0.26	0.28	0.08	0.07
DM2-PMWV	0.14	0.23	0.31	0.18	0.15	0.02
DM3-PMWV	0.07	0.25	0.32	0.13	0.23	0.08
DM4-PMWV	0.16	0.19	0.27	0.25	0.13	0.03
DM5-PMWV	0.07	0.20	0.26	0.34	0.13	0.02
DM6-PMWV	0.14	0.31	0.22	0.14	0.19	0.03
Mean	0.12	0.23	0.27	0.22	0.15	
Minimum	0.07	0.19	0.22	0.13	0.08	
Maximum	0.16	0.31	0.32	0.34	0.23	
Standard Deviation	0.04	0.04	0.04	0.09	0.05	
Disagreement						0.06

Assessment of PV Technologies from Korean PV Manufacturers Worldview (PMWV)				
Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-test Value
Between Experts	0.00	5	0.000	6.2
Between Perspectives	0.09	4	0.023	
Residual	0.07	20	0.004	
Total	0.16	29		
Critical F-value with degrees of freedom 4 & 20 at 0.01 α-level				4.43
Critical F-value with degrees of freedom 4 & 20 at 0.025 α-level:				3.51
Critical F-value with degrees of freedom 4 & 20 at 0.05 α-level:				2.87

TABLE 2: RELATIVE RANKING OF THE PERSPECTIVES IN COMPARISON TO THE BEST (KOREAN PV MANUFACTURERS WORLDVIEW)

Relative Ranking of Perspectives for Korean PV Manufacturers Worldview	Perspective				
	Social	Technical	Economic	Environmental	Political
Mean Relative Value	0.12	0.23	0.27	0.22	0.15
Ratio With Respect to Best Perspective	0.44	0.85	1.00	0.81	0.56

TABLE 3: RELATIVE RANKING OF THE PERSPECTIVES IN COMPARISON TO THE BEST (NORTHWEST US ELECTRIC UTILITY WORLDVIEW)

Relative Ranking of Perspectives for Northwest US Electric Utility Worldview	Perspective				
	Social	Technical	Economic	Environmental	Political
Mean Relative Value	0.14	0.23	0.34	0.19	0.10
Ratio With Respect to Best Perspective	0.40	0.70	1.00	0.60	0.50

VI. CALCULATED TECHNOLOGY VALUES OF CANDIDATE PV TECHNOLOGIES

There is an abundance of existing and new PV technologies with a broad range of performances and claims [2], [17]. For this research the following prominent competing candidate PV technologies were again considered appropriate for a comparative assessment. These include: mono/poly crystalline silicon (c-Si), amorphous silicon (a-Si), cadmium telluride thin film (CdTe), copper indium gallium (di)selenide (CIGS), and organic/plastic PV(OPV).

The results of perspectives' ranking for the Korean PV Manufacturers Worldview were combined with the earlier research results of criteria ranking for each perspective and desirability values for each candidate technology. The theoretical background for the technology value (TV) calculations has been described in reference [9] and the principal formula for the nth technology is presented below.

$$TV_n = \sum_{k=1}^{K} \sum_{j_k=1}^{J_k} p_k \cdot c_{j_k,k} \cdot V(t_{n,j_k,k})$$

The final results indicating the technology value for each of the five PV candidate technologies, with n = 1, 2, 3, 4, and 5, are shown and compared in Table 4, Table 5, and Figure 3. The sub-totals for each STEEP perspective together with cumulative technology value totals for the five PV technologies are also shown. The PV technologies appear to form natural clusters. The highest ranked technologies are c-Si and a-Si with Technology Values of 83 and 82 respectively. The second cluster consists of two established PV thin-films CIGS and CdTe with Technology Values of 76 and 75 respectively. The third cluster has only plastic or organic PV (OPV) with a Technology Value of 62. These three clusters can readily be identified to represent the first three generations of PV technologies.

For comparison purposes the earlier results from the Northwest US Electric Utility Worldview are also presented in Figure 3**Error! Reference source not found.**. It is interesting to note that the PV Technology Values from the two worldviews are very similar; in fact they are almost identical. This is true despite the fact the current worldview represented a Korean entity and the prior worldview was for a US entity.

TABLE 4: TECHNOLOGY VALUES FOR FIVE CANDIDATE TECHNOLOGIES: C-SI, A-SI, CIGS, CDTE, AND OPV (KOREAN PV MANUFACTURERS WORLDVIEW)

PV Technology	Social Perspective (S)	Technical Perspective (T)	Economic Perspective (E)	Environmental Perspective (N)	Political Perspective (P)	Technology Value (TV) (S+T+E+N+P)
c-Si	11	20	19	20	14	83
a-Si	11	19	18	20	14	82
CIGS	9	16	18	19	14	76
CdTe	9	16	18	19	13	75
OPV	9	7	13	20	13	62

TABLE 5: TECHNOLOGY VALUE COMPARISON WITH RESPECT TO THE BEST TECHNOLOGY (KOREAN PV MANUFACTURERS WORLDVIEW)

PV Technology	Technology Value	Comparison to Best Technology
c-Si	83	100%
a-Si	82	99%
CIGS	76	92%
CdTe	75	91%
OPV	62	75%

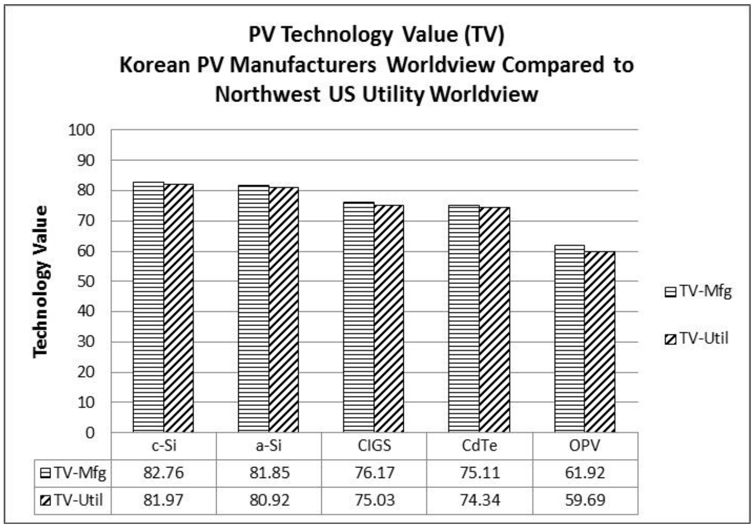

Figure 3: Technology Values for Five Candidate Technologies: c-Si, a-Si, CIGS, CdTe, and OPV
(Korean PV Manufacturers Worldview and Northwest United States Electric Utility Worldview)

VII. CONCLUSION

The results for the Korean PV Manufacturers Worldview indicate that the highest ranked perspective is the economic perspective followed by the technical and environmental perspectives, but these have almost the same priority. The social perspective has the lowest rank. It should be noted that all the five STEEP perspectives have material contribution to the mission of PV technology assessment implying that they are all relatively important. Based on these rankings, the Technology Values for the candidate PV technologies form groupings such that c-Si and a-Si have the highest values at about 83 and 82 respectively. The second group is the thin-film PV group consisting of CIGS and CdTe at 76 and 75 respectively. The last group consists of OPV at 62. These Technology Values are almost identical to those obtained for the Northwest US Electric Utility Worldview in earlier research.

This research validated the use of the HDM model for judgment quantification of decision makers to represent their worldview. Once the underlying HDM is established with the assistance of experts varying worldviews can be researched to obtain technology values for candidate PV technologies.

VIII. FUTURE RESEARCH

The basis of this research is the use of multiple STEEP perspectives and hierarchical decision modeling for the comprehensive assessment of PV technologies. This paper on the PV manufacturers' worldview represents an extension of earlier research that was targeted towards the electric utilities' worldview. Research has been initiated to obtain data with respect to the national policy makers' worldview. This new research is for an African country so the results will provide another dimension of comparative analysis.

As we gain more insights into the global requirements of nations, manufacturers, and utilities, we expect a rich tapestry of future research in this field. This will include, but not be limited to: additions to the criteria under each perspective; assessment of new PV candidate technologies; and the inclusion of big data and data mining.

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APPENDIX: JUDGMENT QUANTIFICATION INSTRUMENT

Solar Photovoltaic (PV) Technology Assessment Using Multiple Perspectives

Use of a Hierarchical Decision Model and Pair-Wise Comparisons to Obtain Relative Importance of Perspectives and Criteria for the Assessment of PV Technologies

Name: ____

1 The mission of this study is to provide a comprehensive assessment of PV Technologies, using five perspectives (Social, Technical, Economic, Environmental, and Political).

To determine the relative importance of the five perspectives with respect to the mission, please compare the elements (perspectives) in each pair below. Allocate a total of 100 points to reflect how many times a perspective is important in comparison to the other. <u>You only need to enter the the value of the 1st element.</u> [Do not enter "0".] The value of the other element will be calculated automatically. Given below are a few examples:

If the 1st element is <u>4 times</u> as important as the 2nd element, enter "80" points for the 1st element. The 2nd element will get 20 points.

If the 1st element is <u>2 times</u> as important as the 2nd element, enter "67" points for the 1st element. The 2nd element will get 33 points.

If the 1st element is the <u>same</u> in importance as the 2nd element, enter "50" points for the 1st element. The 2nd element will also get 50 points.

If the 1st element is <u>1/3 as</u> important as the 2nd element, enter "25" points for the 1st element. The 2nd element will get 75 points.

Social Perspective		vs		Technical Perspective
Social Perspective		vs		Economic Perspective
Social Perspective		vs		Environmental Perspective
Social Perspective		vs		Political Perspective
Technical Perspective		vs		Economic Perspective
Technical Perspective		vs		Environmental Perspective
Technical Perspective		vs		Political Perspective
Economic Perspective		vs		Environmental Perspective
Economic Perspective		vs		Political Perspective
Environmental Perspective		vs		Political Perspective