Use of Multiple Perspectives and Decision Modeling for Solar Photovoltaic Technology Assessment

Nasir J. Sheikh and Tugrul Daim

Abstract As global warming and foreign oil dependence debates grow, more organizations are evaluating renewable energy. Renewable energy generation technologies are complex systems that have wide-ranging implications in their production and deployment. Using multiple perspectives such as social, technological, economic, environmental, and political (STEEP) and their decomposition into multiple criteria or indicators provide a broader yet explicit assessment of the technology under consideration. An effective method of determining the relative importance of a criterion with respect to others is by hierarchical decision modeling and expert judgment quantification instruments. These combined approaches can improve decision making for technology assessment and selection. This paper describes the approach through an example for photovoltaic solar technologies.

1 Introduction

Policies at national and international level are being implemented to incent and support the growth of renewable energy for a variety of reasons including climate change mitigation, fossil fuel pricing, societal demand, and renewable energy pricing heading towards grid parity [1, 3, 4, 17].

Energy technology and deployment planning efforts include energy sourcing and the evaluation of energy conversion devices to meet the desired energy demands in a relative optimal fashion. In today's world an energy planning decision involves a complex process of weighing and balancing diverse socio-political, technical,

N. J. Sheikh (✉)
Portland State University, Portland, Oregon, USA
e-mail: nsheikh@pdx.edu

T. Daim
Portland State University, Portland, USA
e-mail: tugrul@etm.pdx.edu

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economic, and environmental dimensions or perspectives with spatial and temporal considerations. This balancing act is becoming increasing important as nations and peoples are becoming more aware of their rights as responsible citizens and their responsibilities as preservers of the social and natural environments. These dimensions or perspectives are usually represented as multiple criteria (and may include sub-criteria) and may represent conflicting or opposing objectives. These criteria may sometimes be difficult to define and may include quantitative and qualitative sub-criteria or factors [7]. Decision making around energy planning using multiple criteria analysis has been in use for over forty years [19, 24, 27]. Up to the 1970s the most popular criteria was cost, however in the 1980s environmental considerations also became important. Later social aspects were incorporated in the decision analysis and planning process. Political criteria also began to be explicitly recognized through public policies and regulations. Adding to the complexity, renewable energy sources brought further sets of nuances and criteria. This also broadened the scope of evaluations and decision making.

In terms of technology options, these too have increased significantly due to the increase in research and development (R&D) in renewable energy technologies [20, 9, 21]. Public and private sector decision makers now need to assess technologies with respect to a whole range of perspectives and criteria. Better methods are needed for decisions on renewable energy especially since the effect of such technology decisions will be felt for the life of the technology which could easily exceed fifteen to twenty years.

2 Multiple Perspectives and Decision Making

Prior research demonstrated the use of multiple perspectives in many different areas [12–15]. The fundamental concepts can be expanded to be applicable for renewable energy technologies, systems, and processes.

In this paper these renewable energy multiple perspectives are referred to as: social, technological, economic, environmental, and political (STEEP). These perspectives are composed of multiple criteria and each criteria in-turn is composed of multiple sub-criteria (and may be referred to as "factors" for easy distinction). The criteria that relates to each perspective can be stated as follows:

- ***Social Perspective.*** Criteria or factors that impact society—positively or negatively
- ***Technical or Technological Perspective.*** Criteria or factors that relate to technical performance
- ***Economic Perspective.*** Criteria or factors that are indicated by cost of technology diffusion, market adoption, and life-cycle costs ("push–pull-sustenance")
- ***Environmental Perspective.*** Criteria or factors that have an impact on the environment and the earth's natural ecosystems

- ***Political Perspective.*** Criteria or factors that make up political motivation, policies and regulations, market special interests, compliance, and security.

Despite the growing need for energy multiple perspectives, a literature review indicates that studies and findings are limited in scope, cover broad criteria (and not specifics related to renewable energy), have limited capability for operationalization, are project or policy oriented, and have almost no reference to specific renewable energy technologies (especially solar photovoltaic technologies) [29]. Considering all five perspectives for decision modeling and technology assessments in the area of renewable energy generation is a new area of research and may prove to be more effective than using their subset.

A variety of decision making and support tools and methods have been used by energy planners and decision makers for planning, project selection, environmental, and social impact. Reviewing journal literature on energy decision model indicates that the most popular model used is Analytic Hierarchy Process (AHP—a hierarchical decision model) developed by Thomas Saaty [2, 5, 6, 11, 12, 16, 18, 23, 25, 26, 28, 30, 31, 32]. AHP is the most well-known hierarchical decision model (HDM). The HDM model lends itself easily to a layered approach of ranking and prioritizing perspectives and their associated criteria and sub-criteria. Another HDM model developed by Dundar Kocaoglu is utilized by the author for this research [10]. The results from using this HDM model will be very similar to those from AHP.

3 Solar Photovoltaics: Trends

Market research indicates a high growth rate of solar photovoltaic (PV) deployments [8]. The cumulative positive affect of factors such net metering rules, electric rate tariff levels and structures, availability of financial incentives, system pricing, and carbon legislation are evident and will continue to spur growth in PV adoption [22]. [It should be noted that storage and distribution of PV generated electricity is agnostic to solar energy generation technologies].

4 Problem Statement

A comprehensive renewable energy technologies assessment is generally a complex decision problem since there are multiple perspectives (such as the five perspectives referred to earlier) to consider. This complex decision problem can be decomposed or formulated as an analytical hierarchical decision model (HDM) where different perspectives and their associated criteria can be prioritized or ranked. The selection of various levels of criteria (or constraints) can then be applied to address the question, “In the judgment of the decision makers and experts which perspective or criteria are more important than others?" For the purpose of this research, focus is on solar photovoltaic renewable energy technologies.

This is part of ongoing research at the Research Institute for Sustainable Energy (RISE), Department of Engineering and Technology Management, Portland State University, Oregon. The program includes use of HDM for evaluation of criteria, use of desirability functions (similar to utility function) for evaluation of factors, and then technology characterization as a composite of perspectives, criteria, and factors.

5 Methodology

As stated in the problem statement the selected methodology involves an analytical decision model that captures the judgment of the market experts and company's management and subject matter experts.

In effect, the methodology consists of four parts:

- Decision modeling process: building the analytical hierarchical decision Model
- Selecting an expert panel
- Design of judgment quantification instrument (survey questionnaire)
- Expert panel survey.

The decision model with objectives and criteria can be utilized (as a decision tool) to provide direction for the stated problem or decision making.

A *panel* of experts is selected to assist in model development and pair-wise comparison of the perspectives and criteria. The criteria are composed of sub-criteria named as "factors". Experience indicates that 10–15 experts can provide reasonable and balanced results. The experts can have different worldviews or philosophical frames of reference which can heavily influence the results. Hence different strategies can be developed based on the worldviews. These worldviews include (but are not limited to):

- Technology supplier or developer
- Power utility or service provider
- Government policy maker.

5.1 Decision Modeling Process

The decision model is developed by first setting the mission and perspectives for the model and the criteria that would be used to select the most desired target market. This is depicted in Fig. 1.

As mentioned earlier, considering this to be a test case, only the initial results were analyzed.

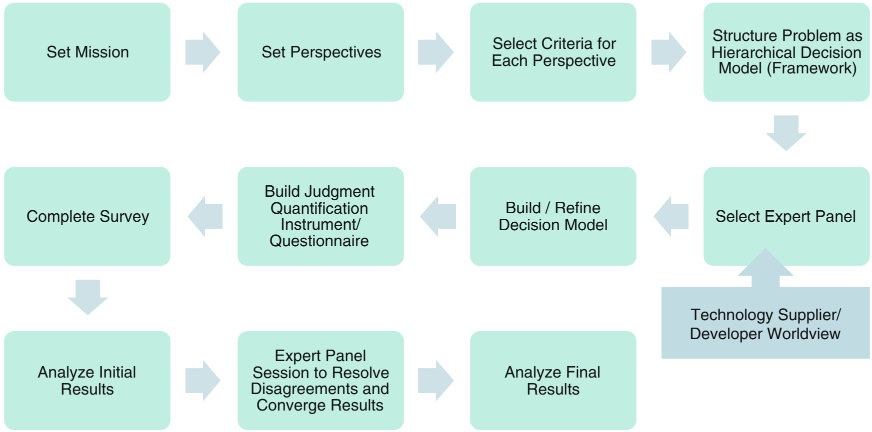

Fig. 1 Decision modeling process

5.1.1 Defining the Hierarchical Decision Model

The objectives, criteria, and sub-criteria (called factors) consisted of the following:

- ***Overall Objective or Mission.*** The ultimate goal of the decision model is to help with a comprehensive assessment of photovoltaic technologies.
- ***STEEP Perspectives.*** To fulfill the mission these five perspectives or dimensions were considered important. These may also be important consideration for worldviews of a technology supplier/developer, power utility or service provider, or government policy maker.
- ***Criteria for Each STEEP Perspective.*** The important criteria or constraints for each objective are listed in Table 1 below as:

Each criterion is composed of multiple sub-criteria or factors. These are listed in Appendix A: Multiple Criteria and Factors for STEEP Perspectives are developed mainly from a literature review [29].

- ***HDM Model.*** The HDM model is shown in Fig 2 and includes the relations between mission, perspectives, and criteria. An enlarged version of this model is shown in Appendix A: Hierarchical Decision Model.

6 Results and Analysis

A group of professional with experience in this area was consulted to quantify the model in this case. The results need to be viewed with demonstration purpose and should not be used to make a decision on these technologies. The objective of this papaer is to demonstrate how to build an evaluation model.

Table 1 Multiple criteria for each STEEP perspective (derived from [29] and expert opinions)

Social	Technical	Economic	Environmental	Political
Public perception	Efficiency	Product costs	Pollution/negative impact	Policies
Employment	Technology maturity	LCOE (Electricity generation costs)	Environmental benefits/ positive impact	Regulation/ deregulation of power markets
Health and safety	Production/ operations	Financial analysis	End-of-life/ disposal	Public/Government R&D framework
Local infrastructure development	Resources/ materials required	Cost mitigation	Consumption of resources	Codes/standards—compliance
	Deployment	Market adoption		Perception/position of utilities
	Maintenance/ warranty	Positive impact on local economy		Security
	Codes/ standards—development			
	Technology roadmap			

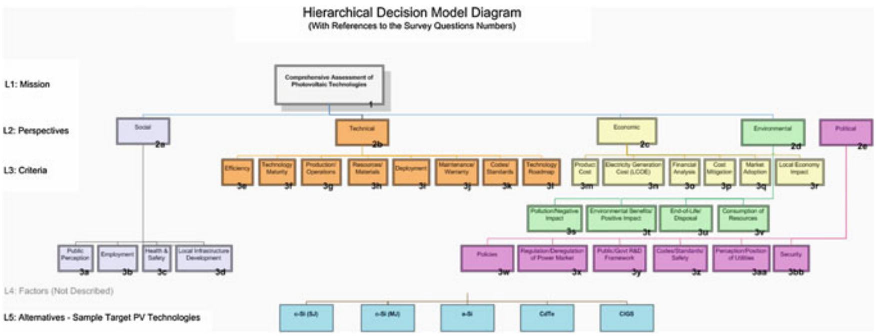

Fig. 2 Hierarchical decision model diagram

The initial composite results for eight "technology supplier/developer world-view experts" are shown in Figs. 3, 4, 5, 6, 7, 8, 9. The initial results for this group indicated that all the multiple perspectives were important from an overall assessment point of view. The importance of the perspectives to the mission are relatively balanced ranging from relative values of 0.19–0.22. [The total is 1.00 for all five perspectives].

Evaluating and ranking the criteria for each perspective showed a certain level of variation, however, again, no one or group of criteria was dominant or stood out.

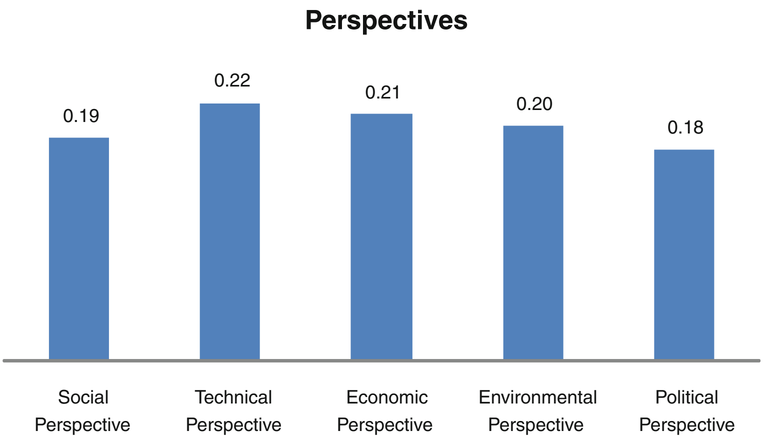

Fig. 3 STEEP perspectives

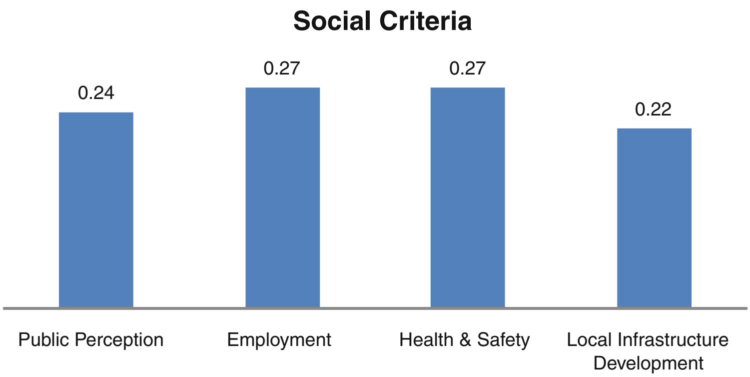

Fig. 4 Social perspective

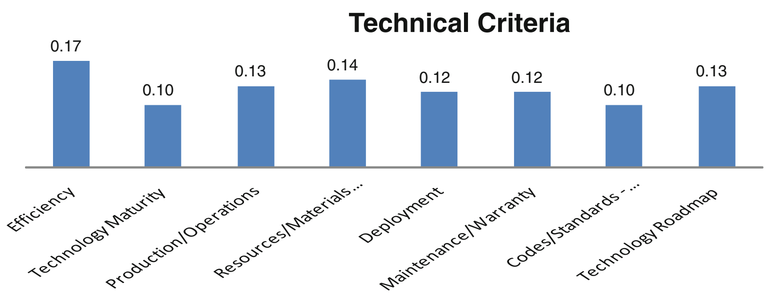

Fig. 5 Technical perspective

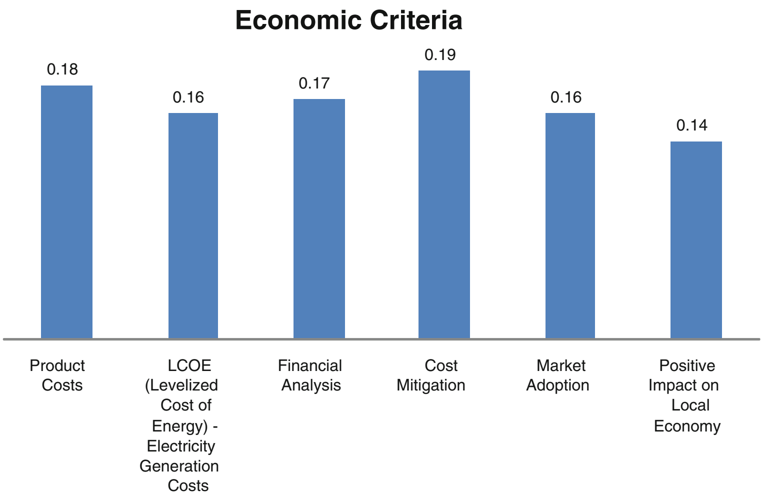

Fig. 6 Economic perspective

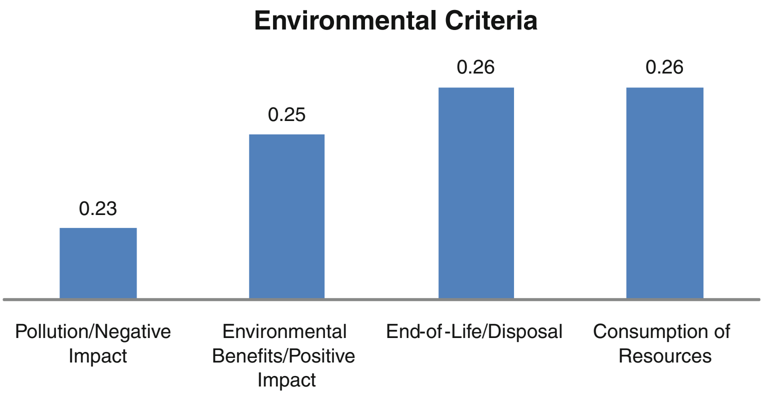

Fig. 7 Environmental perspective

The following table (Table 2) lists the highest and lowest criterion/criteria for each perspective.

This HDM is very useful for ranking the importance of perspectives and criteria for PV technology assessment. However, it has some limitations, such as:

- It should be noted that this approach although useful to gain insight into ranking of perspectives and criteria is based on the worldview of the experts and hence reflects their worldview biases. So its scope will be useful for that particular worldview. For example, the initial results reflect the worldview of a group of technology developers.

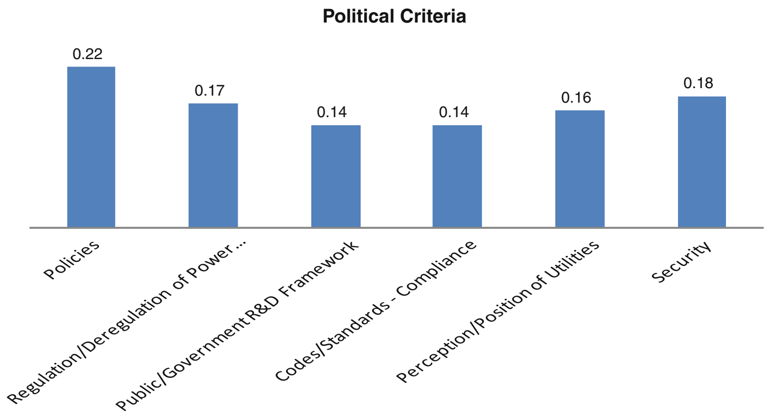

Fig. 8 Political perspective

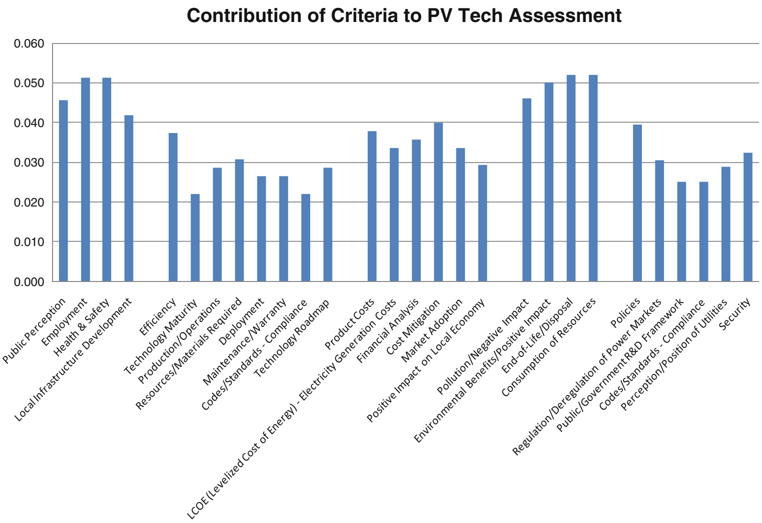

Fig. 9 Contribution of STEEP perspectives and related criteria to PV technology assessment

- The above judgment quantification survey is one approach. Another approach may be as follows. Experts would only address the pair-wise comparison of criteria related to the perspective that is their domain of expertise. For example, technologists would only compare the criteria under the Technical Perspective, social scientists would only compare the criteria under the Social Perspective, environmental scientists would only compare the criteria under the Environmental Perspective, etc. Separately, the top five STEEP perspectives may be ranked by high level decision makers. Then all the sets of results can be combined for the final HDM analysis.

Table 2 Highest and lowest criteria in relative importance to each perspective

Perspective	Highest criteria	Lowest criteria
Social	Employment, health and Safety	Local infrastructure development
Technical	Efficiency	Technology maturity, codes/standards development
Economic	Cost mitigation	Positive impact on local economy
Environmental	End-of-life/disposal, consumption of resources	Pollution/negative impact
Political	Policies	Public/Government R&D framework, codes/ standards compliance

- Other approaches for PV technology assessment may be simpler such as using only those top perspectives or criteria that are considered important by the industry or targeted worldview.

7 Conclusion

Initial results indicate interesting outcomes and provide insights into the actual explicit judgments of experts. (Refer to the section above). The initial results also helped in the clarification (or correction) of assumptions such as the Technical Perspective should be most important for those with a technology supplier or developer worldview. The initial results indicated that this may not be case (and in fact indicated that all five perspectives are relatively important) although more surveys are needed to validate or modify the findings.

The HDM model is a good method to obtain explicit judgments to better understand what is truly important for decision makers and experts. This model has the capability to be flexible and scalable with respect to multiple perspectives, multiple actors (decision makers, stakeholders, practitioners, end users, etc.), multiple criteria, and ability to provide guidance to practitioners and operational management. Hence it can provide assessment and direction. The HDM model helped in assessing both individual and group rankings of the perspectives and criteria for better analysis and indications for improvements of the survey.

8 Future Research

Although initial results indicated that all five STEEP perspectives were important more research is needed to test out the some of the scenarios and cases mentioned in the Initial Results and Analysis section above. Gaining insight into what is required for next steps would be more difficult without the use of HDM. Through further surveys and analyses we will be able to arrive at a robust evaluation of the criteria and perspectives. Another step would be to determine desirability functions for each sub-criteria or factor. The PV technology value (or score) can then be characterized by the composite of perspective, criteria, and factor values. This PV technology value could then be compared to the ideal value and also to its peer technologies. It is the intention of the author to pursue these future avenues of research to develop the model, analyses, and results further taking into account the initial findings from this study.

Appendix A: Multiple Criteria and Factors for STEEP Perspectives

Technical Perspective

Efficiency
- Module energy efficiency
- Cell energy efficiency
- Energy efficiency
- Inherent system efficiency
- Thermal efficiency
- Heating value
- PV system yield
- Reference yield
- Performance ratio
- Energy density

Technology maturity
- Density/maturity of patents and publications
- Identify positive trends
- Ability to bridge technology gaps
- Flexibility/scalability
- Modularity
- Obsolescence resistant

Deployment
- Large-scale/power plant installation
- Field testing/evaluation/performance
- Service availability (uptime of PV system)
- Reliability
- Power purchase agreements (PPAs)
- Optimized to utility scale
- Impact on meeting important energy targets
- Suitable for BIPV (Bldg integrated PV)
- Storage
- Transmission
- Distribution

Production/operations
- Production capacity
- No. of process steps (production processes complexity)
- Leverage mature production processes (e.g. from chip mfg)
- Chemicals/gases waste
- Wafer thickness
- Line breakage
- Production maturity

Maintenance/warranty
- Low maintenance
- Long lifetime (20 + years)
- Annual degradation warranty
- Management of environmental factors (dust, debris, etc.)

Codes/standards—compliance
- US code
- National/international standards
- Building/environmental safety standards

Technology roadmap (2010–2030)
- PV technology (cell/module)
- PV technology patents/publications maturity and trends
- Inverter and BOS (balance-of-system)

(continued)

Resources/materials required • Avoid use of rare metals (e.g. indium) • Avoid hazardous materials (e.g. cadmium) • Resource availability/access • Chemicals, gases, etc.	

Social Perspective

Public perception • Aesthetics • Visual Impact • Heterogeneous interests, values, and worldview • Engagement in public policy • Conflict with planned landscape • Synergistic with quality of life improvement policies • Impact of lifestyle • Easy/convenient to use • Legacy for future generations • Social benefits • Social acceptance • Impact on property values • Impact on tourism **Employment** • Job creation • Addition to employment diversity • Availability of workforce • Poverty alleviation • Increase in production employment • Increase in total employment	**Health and safety** • Public safety • Work safety • Hazardous health effects (accidental, long-term) • Investment in health of society (indirect) **Local infrastructure development** • Development/improvement of infrastructure • Support of related industry • Contribution to regional/local improvement • Regional/local empowerment

Economic Perspective

Product costs • Capital (amortized) • Startup (amortized) • Materials • Direct production • Sales and marketing • R&D/engineering • Administrative • Facilities • Warranty/maintenance	**Cost mitigation** • Independent of Economies of Scale • Energy Supply Chain Advantage (e.g. against fuels) • Reduction of Administrative Costs (e.g. against imports) • Reduction in Subsidies (of fuels) • Reduction in Military Costs (for energy) • Better Use of Hard Currency (for Developing Countries)

(continued)

- Inverter and BOS (balance-of-system)
- Installation
- Disposal/recycle (end-of-life)

Levelized cost of energy—electricity generation costs

- Excluding plant end-of-life shutdown/ disposal
- Including plant end-of-life shutdown/ disposal

Financial analysis

- Cost/benefit
- ROI (return on investment)
- EPBT (energy pay back time–energy viability)
- LCOE*
- Savings to power utilities
- Portfolio costs to utilities
- Costs trends/roadmap: 2010–2030
- Risk mitigation

Market adoption

- Market maturity
- Product/technology maturity
- Supply chain maturity
- US Code compliance
- Economic multiplier effect (through use of product)
- Customer willingness to pay

Positive impact on local economy

- Higher wage jobs
- Creation/expansion of economic clusters
- Job creation

Creating insourcing trend (versus outsourcing)

Environmental Perspective

Pollution/negative impact

- GHG (Green house gases—affecting climate change)
- Particles (smoke, dust, etc.)
- Vapor
- Visual/glare
- Water
- Noise
- Solid waste
- Water resources
- Stratospheric ozone
- Soil
- Natural habitat
- Water temperature change
- Wind pattern change
- Forest and ecosystem
- Ecological footprint (crops, woods, etc.)
- During production phase
- During deployment phase
- Accidental release of chemicals

Environmental benefits/positive impact

- Better land utilization
- Climate change mitigation
- Environment sustainability
- Low land requirement
- Energy conservation improvement
- Better consumption of natural resources
- Reduced fossil fuel imports/dependence
- Better use of rooftops

End-of-life/disposal

- Biodegradability
- Easy recyclability
- Leverage mature production processes (e.g. from chip mfg)
- Chemicals/gases waste

Consumption of resources

- Land
- Water
- Materials

Political Perspective

Pollution/negative impact	Environmental benefits/positive impact
• GHG (Green house gases—affecting climate change)	• Better land utilization
• Particles (smoke, dust, etc.)	• Climate change mitigation
• Vapor	• Environment sustainability
• Visual/glare	• Low land requirement
• Water	• Energy conservation improvement
• Noise	• Better consumption of natural resources
• Solid waste	• Reduced fossil fuel imports/dependence
• Water resources	• Better use of rooftops
• Stratospheric ozone	**End-of-life/disposal**
• Soil	• Biodegradability
• Natural habitat	• Easy recyclability
• Water temperature change	• Leverage mature production processes (e.g. from chip mfg)
• Wind pattern change	• Chemicals/gases Waste
• Forest and ecosystem	**Consumption of resources**
• Ecological footprint (crops, woods, etc.)	• Land
• During production phase	• Water
• During deployment phase	• Materials
• Accidental release of chemicals	

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