INTRODUCTION AND OVERVIEW

Project Background

Since its inception in the 1970s, the U.S. Department of Energy (DOE) has operated a substantial program in the development and encouragement of renewable energy technologies. As part of its ongoing effort to document the status and potential of these technologies, DOE, along with its national laboratories and support organizations, developed the first set of Renewable Energy Technology Characterizations (TCs) in 1989. The TCs were designed to respond to DOE's need for a set of consistent cost and performance data to support the development of the biennial National Energy Policy Plans. That first set of TCs was subsequently used to support the analyses that were performed in 1991 by DOE for the National Energy Strategy. The TCs were updated in 1993, but until now had not been formally published and existed only in draft form.

The Electric Power Research Institute (EPRI), operating on behalf of its member utilities, has conducted a program in the assessment, evaluation and advancement of renewable power technologies since the mid-1970s. In that role, EPRI has been called upon by its members, and often by the energy community in general, to provide objective information on the status and outlook for renewables in prospective electric-power applications. Toward that aim, EPRI has joined with DOE to produce this set of Renewable Energy Technology Characterizations.

This joint project is one of a number of activities that DOE and EPRI are conducting under the joint DOE-EPRI Sustainable Electric Partnership entered into formally by both organizations in October 1994. It builds upon a number of activities conducted jointly by DOE and EPRI over the past two decades.

Objectives, Approach and Scope

Purpose and Audience: In response to growing interest in renewable power technologies and the need for consistent, objective assessments of technology performance and costs, DOE and EPRI collaborated to prepare the Renewable Energy Technology Characterizations (TCs) presented in this document. Together, through this document, DOE and EPRI aim to provide for the energy community and the general public an objective picture of the status and expectations for the renewable power technologies in electric-power applications in the United States. These TCs represent a consensus between DOE and EPRI on the current status and projected development path of five renewable electricity generating technologies: biomass, geothermal, photovoltaics, solar thermal and wind. In addition, recognizing the role that storage can play in enhancing the value of some renewable power plants, a TC for storage technologies, with a strong emphasis on batteries, is included in an appendix. The TCs can serve two distinct purposes. First, they are designed to be a reference tool for energy-policy analysts and power-system planners seeking objective cost and performance data. Second, the extensive discussions of the assumptions that underlie the data provide valuable insights for R&D program planners as they strive to prioritize future R&D efforts.

Approach: Building on the best available information and experience from many years of direct involvement in the development and assessment of renewable energy technologies, experts from DOE, its national laboratories and support organizations prepared characterizations of the major renewable technologies. These were subjected to in-depth review by EPRI technical staff in renewables and selected outside reviewers, and then discussed at length in two technical workshops involving the writers and the reviewers. The characterizations were then revised, reflecting discussions at and subsequent to the workshops, resulting in this consensus document. In some cases, EPRI staff participated in preparation of overview sections.

Document Scope: The TCs do not describe specific products or hardware configurations. They describe typical system configurations at five year increments through the year 2030, based on a projected evolution of the technologies during that timeframe. They often portray changes in expected technology configuration over time. Allowing a changing configuration ensures that, in each timeframe discussed, the TC represents the most cost-effective configuration projected to be available in that timeframe. For example, the solar thermal power tower evolves from a hybrid plant with a conventional receiver to a solar-only plant with an advanced receiver. The TCs do not attempt to pick winners among a variety of choices. In that spirit, thin film PV systems are, for example, described only in a generic way, not specifying any particular thin film technology in any given timeframe. This view of the technology future mirrors the R&D portfolio approach that DOE takes, allowing the technology itself and the marketplace to determine winners and losers.

Each TC should be thought of as a description of that technology in a particular application, typically as a grid-connected system for bulk power supply. However, some TCs do briefly describe other applications that could use substantially the same technology configuration.

These TCs differ from EPRI's Technical Assessment Guide (TAG™) in that they provide more extensive discussions of the expected technology evolution through 2030. However, the cost and performance data presented here are being used as a basis for TAG™ revisions that are currently in progress.

Similar to the TAG™, these TCs do not describe a recommended economic analysis methodology, but instead describe various approaches that could be taken to calculate levelized cost of energy or other appropriate financial figures of merit. These approaches span a range of possible ownership scenarios in a deregulated utility environment.

Cautionary Note: The cost and performance information presented represent the best judgments of the individuals involved in the preparation and review of this document. As these technologies enter the commercial marketplace, normal competitive forces and commercial experience may have impacts that are difficult to predict at this time. For example, there are indications that prices for some conventional power-plant components and associated engineering services are dropping as competition in power generation becomes more widespread. Based on very recent commercial experience, this trend is already reflected in the geothermal-hydrothermal flash-steam plant costs presented in this document. Similar cost impacts may be observed in other renewable power plants employing conventional thermal-generation components once the technologies become established sufficiently to attract multiple commercial suppliers. Readers are urged to use caution in applying numerical data from this document in commercial situations without consulting engineering firms actively involved in the commercial marketplace.

Relationship to Ongoing Renewables Programs at DOE and EPRI

The technologies discussed in this document are considered by the renewables community, and by the managements of the DOE and EPRI renewables programs, to have good potential for contributing significantly to the U.S. electrical energy supply. Consequently, these technologies continue to receive technical and market-development support within the programs of DOE and EPRI. Of course, there is no guarantee that all of these technologies will develop and contribute as projected in this document. Rather, their individual prospects and roles will depend not only on the degree of support received, but also on the pace of progress and on societal needs and priorities. Ultimately, the marketplace, reflecting both commercial and societal forces, will decide.

Development-Support Assumption

The projected progress for these technologies is based on the assumption that robust programs continue in both technology and market development. In general, these programs need both public and private sector support, with the balance shifting more toward the commercial sector as technical maturity is approached. If support for a particular technology is curtailed, then the projected progress almost certainly will not occur.

Generic Benefits and Issues

The benefits of using renewable energy resources are many. Most of these benefits arise from their virtually inexhaustible nature. Solar and wind resources are replenished on a daily basis. Biomass can be grown through managed agricultural programs to provide continuous sources of fuel. Geothermal power is extracted from the virtually unlimited thermal energy in the earth's crust.

Renewable energy resources are broadly available across the U.S. Certain regions, however, tend to have more accessible resource of one type than another. Figure 1 illustrates this diversity. For example, in the Midwest, biomass and wind resources are excellent, as is the solar radiation needed for flat-plate photovoltaics. In the Southwest, high levels of direct normal insolation are ideally suited to solar thermal and sunlight-concentration photovoltaic technologies. Geothermal resources are concentrated in the western parts of the U.S. The availability of each of the renewable resources is explored further in the technology overviews in this document.

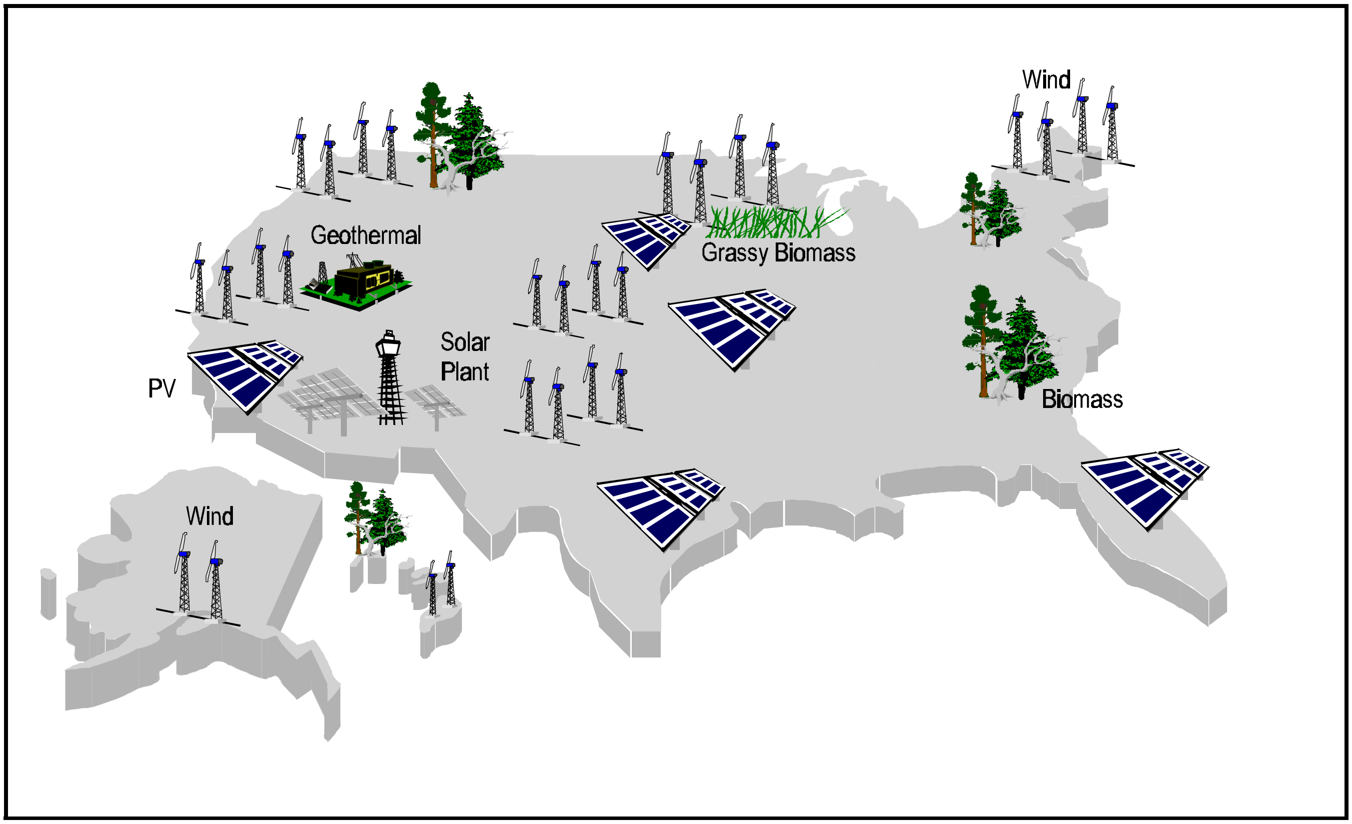

Figure 1. Diversity of renewable energy resources in the United States.

The benefits of renewable energy extend beyond abundance and diversity. As indigenous resources, they foster both local control and economic growth. An investment in renewable energy contributes to local economic security. In addition, the incorporation of renewables in a generation portfolio may reduce the risks associated with fluctuating fossil-fuel prices and supplies.

As renewable energy technologies become more cost-competitive, their true economic benefits are being realized. Since many renewable energy plants do not need to be built in large scale to achieve the lowest possible plant costs, they can be built in size increments proportionate to load growth patterns and local needs. This is often referred to as their modularity. Given their smaller size, they can also be located closer to the customer load, reducing infrastructure costs for transmission and distribution, and helping to guarantee local power reliability and quality. Such "distributed" applications appear to have a potentially high economic value beyond just the value of the electricity generated.

Several of the renewable energy technologies, namely photovoltaics, solar-thermal and wind, produce no emissions during power generation. Biomass plants, with a properly managed fuel cycle and modern emission controls, produce zero net carbon emissions and minimal amounts of other atmospheric effluents. The situation is much the same for geothermal plants. When these technologies displace fossil fuels, they avoid emissions that would otherwise be generated. With the growing concern about climate change and carbon emissions, renewable energy technologies can be significant contributors to global efforts to reduce greenhouse-gas emissions.

The value of renewable-generated electricity is determined in part by the time of day at which the electricity is delivered to the grid and also by the probability that it will be available when needed. For example, solar output tends to follow utility summer-peak loads in many locations. Because power delivered during peak periods is more valuable to the utility system, renewable energy technologies can provide high value electricity and can be significant contributors to a reliable power supply system at critical times in those regions. Biomass, geothermal and fossil-hybrid renewable systems are fully dispatchable and compete most closely with conventional fuel-based systems. In some cases, such as the solar-thermal power tower with hot salt storage, energy-storage capability may be included economically. In these cases, the degree of dispatchability achieved depends on the amount of storage included. Intermittent systems, such as wind and solar without storage, will have value as determined primarily by the time of day and year at which electricity output is available.

Further discussions of the issue of value are contained throughout this document. It is important to realize that the proper use of financial models to determine project attractiveness requires accurate projections about the value to customers of the power from that system. In most cases, the relative merit of a particular renewable power technology is not determined solely by a levelized cost of energy.

Overall Perspectives on the Renewable Technologies

While each of the characterized renewable technologies is discussed in detail in this document, the following summary presents an overview of current status and applications for each.

<u>Biomass:</u> The use of forestry and agricultural residues and wastes in direct-combustion systems for cogeneration of electricity and process heat has been a well-established practice in the forest-products industry for many years. Use of these feedstocks in utility electric power plants has also been demonstrated in several areas of the country with access to appropriate fuels, in general with acceptable technical performance and marginal economics. The marginal economics are due to the small size of many of the existing plants and the consequent high operating costs and low efficiencies. Also, fuel shortages have often driven fuel prices up and made operation too expensive. The larger-sized plants, in the 50 MW_e range rather than the 10-to-25 MW_e size range of many projects built in the 1980s, have economics that are acceptable when fuel costs are close to \$1/MMBtu, or when steam or heat from the direct-combustion biomass boiler is also a valued product. In addition to activity with current technology, development is proceeding on advanced direct-combustion systems.

One technology can use direct combustion of biomass fuels today without incurring the capital expense of a new boiler or a gasification/combined-cycle system. This technology is biomass co-firing, wherein biomass is co-fired, or burned together, with coal in existing power plants. Though it does not increase total power generation, this mode of operation can reduce power-plant emissions and serve as a productive use for a waste stream that requires disposal in some way. Co-firing can be carried out as a retrofit, often with very low incremental capital and O&M costs. Biomass co-firing has been successfully demonstrated in a number of utility power plants, and is a commercially available option in locations where appropriate feedstocks are available.

Biomass gasification and subsequent electricity generation in combustion-turbine or combined-cycle plants is also being pursued. This mode of operation can be more attractive than direct combustion because of (a) potentially higher thermal efficiency, (b) the ability to maintain high performance in systems over a wide range of sizes from about 5 MW to about 100 MW, and (c) increased fuel flexibility because of opportunities to reduce unwanted contaminants prior to the power generation stage. These systems are in the development and demonstration phase. The key issue requiring successful resolution is sufficient cleanup of the biogas so that turbine damage is avoided. The gas must be cleaned of alkalis to gas-turbine-entrance standards, and this cleanup must take place in an environment that is prone to tar formation.

Geothermal: Commercial electricity from geothermal steam reservoirs has been a reality for over 30 years in California and Italy. However, steam reservoirs are rare and have already been exploited, at least in the developed countries. Of greater potential in both developed and developing countries are geothermal-hot-water, or liquid-dominated-hydrothermal, resources. A number of hydrothermal plants, perhaps 30 to 40, both developmental and commercial, have been built and are in operation. Some use conventional steam-separation and steam-cycle power-plant equipment, while others employ a binary cycle that takes advantage of working fluids with lower vaporization temperatures than water. Commercial attractiveness depends largely on the quality of the hydrothermal resource: temperature of the hot water, permeability of the rock formation, chemistry of the hot water, and necessary drilling depth. To ascertain this quality, wells need to be drilled. Since the outcome is not assured prior to drilling, locating suitable resources presents a major commercial risk.

Another geothermal-power approach is in the research stage. This involves drilling deep holes (one-to-five kilometers) to reach hot dry rock that is close to locations where magma or other hot intrusions from the molten mantle of the Earth come unusually close to the surface. In this context, “dry” rock implies that no natural water source is associated with the hot rock, unlike the situation in the hydrothermal case. Water from a surface source would be injected, heated, used in a steam- or binary-power cycle, and then re-injected for recycling. If successful, this approach could make available a huge resource relative to present geothermal resources. However, technical uncertainties and risks are very high, so the commercial potential of this approach cannot be estimated accurately today.

Photovoltaics: Photovoltaic power systems convert sunlight directly into electricity through a solid-state-electronic process that involves no moving parts, no fluids, no noise and no emissions of any kind. These features are attractive from operating, maintenance and environmental standpoints, and have positioned photovoltaics to be the preferred power technology for many remote applications both in space and on the ground. Relative to conventional grid power, photovoltaic electricity is some five-to-ten-times more expensive. Hence, it is currently used in locations or applications where utility distribution lines are not readily available. Newer, potentially lower-cost photovoltaic technology is emerging from ongoing industry-government research and development programs, and its use in commercial and demonstration applications is beginning.

Although increasing use could occur more rapidly in some developing countries, grid-competitive photovoltaic electricity is probably ten-to-twenty years off in the developed world. However, interest is growing in a new mode of photovoltaic deployment, called building-integrated, where the photovoltaic cells or modules become integral to structural, protective or cosmetic elements of a building such as roofs and facades. In these applications, the high cost of the photovoltaic components is partially masked by the cost of the building elements, and the decision to employ photovoltaics is made on the basis of such factors as aesthetics and social conscience rather than cost of electricity alone. Many believe that this commercial entry strategy will ultimately succeed in reducing photovoltaic costs through production experience to the point where they can approach costs of grid power. Several governments and many communities in the developed world are incentivizing these applications based on this belief. Because of the growing prominence of building-integrated and other on-site applications of photovoltaics, a section on residential rooftop photovoltaic systems is included in this document.

Another approach to power plants employing photovoltaics uses concentrated sunlight in conjunction with unusually high-performance photovoltaic cells. While attractive technical performance has been demonstrated in some instances, an early market for these systems has not materialized. Unlike flat-plate photovoltaic systems that have established themselves in remote power applications, the potentially high-performance concentrator systems have not yet established a track record in the field. This, coupled with the need to build relatively large systems (at least several tens of kW) to realize their cost advantage and the added complexity associated with required sunlight tracking, has seriously hampered market entry up to now.

Solar Thermal: Solar thermal power systems use concentrated sunlight to heat a working fluid that generates electricity in a thermodynamic cycle. Three general approaches have received development attention. The first, called the central-receiver or power-tower configuration, employs a field of mirrors that track the sun and reflect sunlight to a central receiver atop a tower. The working fluid is circulated through and heated in the receiver, and is then used to drive a conventional turbine. The fluid and its thermal energy can be stored to decouple the collection of the solar energy and the generation of electricity, enabling this power plant to be dispatched much like conventional thermal power plants. This is an attractive feature to electric utilities and power system managers. Several experimental and demonstration power-tower systems have been built; and one, employing thermal storage, is currently under test and evaluation in California. As yet, the commercial prospects for this approach cannot be accurately projected.

Another approach employs parabolic dishes, either as single units or in fields, that track the sun. A receiver is placed at the focal point of the dish to collect the concentrated solar energy and heat the system's working fluid. That fluid then drives an engine attached to the receiver. Dish systems also have potential for hybridization, although more developmental work is required to realize this potential. In contrast to the other two approaches, which are targeted at plants in the 30 MW and higher range, and which use a single turbine-generator fed by all of the solar collectors, each dish-receiver-engine unit is a self-contained electricity-generating system. Typically, these are sized at about 10 to 30 kW. Hence, a larger power plant is obtained by employing a number of these units in concert. With some interruptions due to changing market conditions, dish systems using Stirling engines have been deployed, with both public and private support, for experimental and demonstration purposes since the early 1980s. Current development and demonstration activities are aimed at key technical and economic issues that need to be resolved before commercial prospects can be clarified. Stirling-engine development for prospective vehicular applications is also under way. If successful, transportation sector market penetration would substantially improve the commercial outlook for solar dish-Stirling systems.

The third approach employs a field of sunlight-tracking parabolic troughs that focus sunlight onto the linear axis of the trough. A glass or metal linear receiver is placed along this axis, and a working fluid is circulated through and heated in this receiver. The fluid from a field of troughs passes through a central location where thermal energy is extracted via a heat exchanger and then used to drive a conventional turbine. This configuration lends itself well to hybrid operation with fossil fuel combustion as a supplemental source of thermal energy.

In the early 1980s, federal and California-state financial incentives were established to encourage the commercial deployment and use of emerging renewables. Two technologies were in a position to benefit from these incentives: solar thermal troughs and wind turbines. Trough systems were deployed on a commercial basis in the 1980s and early 1990s, and continue to operate today. In addition to the government-tax-credit incentives, these plants were partially supported by above-market energy payments that are no longer available. Hence trough systems have not been offered commercially since 1991. Should conventional energy costs rise to the above-market support levels of the late 1980s (when significant increases in oil prices were being projected), or should significant incentives for renewable energy arise in the near future, trough technology would be available to play an important role in areas with good sunlight. In addition, efforts are underway to revive this technology for use in developing countries that have urgent needs for new electric power sources, such as India and Mexico.

Although the solar-thermal trough (and wind) systems fielded in the early 1980s experienced considerable technical difficulties, the overall result of the deployments of the 1980s and the associated experience and technical development was that both trough systems and wind systems (see wind discussion below) had achieved technical and commercial credibility by the early 1990s. Energy costs from these systems were approaching the competitive range for grid power. Trough-energy costs were somewhat higher than wind-energy costs; but, owing to hybridization with natural gas, the trough plants were dispatchable. Hence their energy had higher value in some instances. Wind energy, in contrast, was available only when the wind blew.

Wind: As mentioned above, wind power systems progressed substantially as a result of the 1980s government incentives, with a steady trend of cost reductions throughout the 1980s. Since 1990, the cost of energy from the wind has continued to decline, due to continued deployment and to public-private development programs in the U.S. and, to an even greater extent, in Europe. Wind power is now on the verge of becoming a commercially established and competitive grid-power technology. Although expansion of the U.S. wind market has been slowed since the onset of electric-sector restructuring in 1995, the wind markets in Europe and elsewhere in the world have continued to grow, led by firms in Denmark and Germany. The growth of wind in Europe has been fueled, in part, by aggressive goals for renewable power deployment in response to strong public and political support for clean energy and growing concern over global climate change. And there are signs that the pace of wind deployment in the U.S. is again on the rise.

With the exception of the Southeast, most regions of the U.S. have commercially attractive winds. In addition to wind resource quality, other issues that need to be considered, as with most commercial power plants, are transmission requirements and potential environmental impacts. Most U.S. wind facilities installed to date are wind farms with many turbines interconnected to the utility transmission grid through a dedicated substation. There is growing interest in distributed wind facilities, with a small number of turbines connected directly to the utility distribution system without a substation. Such installations account for more than half of the over 4,000 MW of wind in Europe, but the U.S. to date has little experience with this mode. Hence this document focuses on central-station wind applications.

The great majority of wind power experience has been obtained with the traditional wind turbine configuration, in which the rotor revolves about a horizontal axis. In addition, several development programs of the past twenty years have focused on turbines with rotors that turn about a vertical axis (sometimes called "egg-beater" turbines). Although the case cannot be considered completely closed, the weight of experience indicates strongly that the vertical axis machines will not show a performance or commercial advantage relative to the horizontal axis machines. Hence development of the vertical axis units has all but halted, and this document focuses entirely on horizontal axis turbines.

Energy Storage: Recent advances in batteries and other storage technologies have resulted in systems that can play a flexible, multi-functional role in the electricity supply network to manage power resources effectively. The current electricity market offers a number of opportunities for energy storage technologies in which storage of a few seconds to a few hours of electricity is valuable. These systems can be located near the generator, transmission line, distribution substation, or the consumer. Improved, low-maintenance, spill-proof, relatively compact lead-acid batteries are commercially available today.

Energy storage systems are used beneficially today in a variety of applications. Examples include mitigation of power-quality problems and provision of back-up power for commercial/industrial customers, utility substations, and transmission-line stability. In addition, energy storage can play an important role in enabling the increased utilization of intermittent renewable energy sources such as wind and photovoltaics. In grid-connected applications, the storage system can be charged from the renewable source or from the utility grid, whichever is economically preferred.

Document Overview

The five main chapters of this document correspond to five categories of renewable electricity-generating technologies -- biomass, geothermal, photovoltaics, solar thermal, and wind. Each of these five chapters has an Overview that discusses key development and deployment issues for that technology category. Each chapter has one or more Technology Characterizations (TCs); e.g., there are TCs for hydrothermal and hot dry rock systems within the geothermal technology category. Each TC was prepared in the format outlined in Figure 2. In addition, energy storage is characterized in an appendix that follows the same format.

Chapter 7 provides a discussion of financial analysis techniques. The chapter also provides estimates of levelized cost of energy using these techniques.

Technology Characterization Outline

1.0 System Description: This section begins with a detailed graphic depicting key components and subsystems. A system boundary is shown, drawn around any required substation or other required grid interface equipment. The section includes a detailed discussion of the major system features, and how the system depicted in the schematic operates.

2.0 System Application, Benefits, and Impacts: This section contains a description of the applications for which the given system is designed. The motivation for developing the system is given, as is a description of the energy service provided by the system. Also delineated are the potential economic and environmental benefits and impacts.

3.0 Technology Assumptions and Issues: This section includes an explanation of current technological status and the anticipated progression of the technology through the year 2030. It also includes assumptions concerning the system being characterized, including location, commercial readiness, resource assumptions, and the energy service that the system provides. Perspectives on R&D efforts needed to ensure future progress are also presented.

4.0 Performance and Cost: This section contains the primary data table describing current (1997) and projected future (through 2030) technology cost and performance.

4.1 Evolution Overview: This subsection provides a short description of how the baseline system's configuration, size and key components evolve over the period.

4.2 Performance and Cost Discussion: This section provides a detailed discussion to explain and justify the projections made for the technical performance and cost indicators in the table found in Section 4.0. Assumptions, methods, rationale, and references are also provided.

5.0 Land, Water, and Materials Requirements: This section contains a table and short discussion regarding the land and water requirements for the technology. It also includes a listing of any materials considered unique to the technology (e.g., cell raw materials, catalysts).

6.0 References: A complete list of the literature cited is included.

Figure 2. Outline for Technology Characterizations