Summary Report on the DOE Workshop On a Systems-driven Approach To Inverter Research and Development

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Sponsored by:

The U.S. Department of Energy

Solar Energy Technologies Program

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Table of Contents

ABSTRACT

This report provides a summary of the DOE Workshop for a Systems-driven Approach To Inverter Research and Development that was sponsored by the U.S. Department of Energy Solar Energy Technologies Program. The workshop was the third in a series of DOE-sponsored workshops that focus on applying the systems-driven approach to align DOE-sponsored development efforts with market specific requirements. The approach applies a consistent methodology to develop and use analytical tools to determine the impact of R&D endeavors and non-R&D activities on the costs and impacts of the Solar Energy Technologies Program. The goals of this workshop were focused on collecting consensus directions from a mix of inverter industry, consumer industry and DOE program leaders related to using the approach in inverter development. The participants provided defined and specific inverter requirements, expectations and targets as well as common elements for inverters for solar and distributed energy generation programs. The common needs are an important aspect of the consensus results since they may be used to guide collaborative efforts among the different DOE programs and help find ways to avoid duplication of efforts to improve the effectiveness of scarce R&D funds. A second goal was to assemble information and needs that can be used to develop the basic framework for a "DOE 5-year Plan For Inverter Research and Development."

1 Executive Summary

On April 23 and 24, 2003 a group of 64 strategic participants concerned with the manufacture, applications and development of inverter technologies convened at the Maritime Institute of Technology in Linthicum, Maryland to address concerns and issues associated with applying a systems-driven approach to DOE-sponsored inverter research and development.

The strategic participants from the inverter industry, the energy source industry, install/system organizations, universities, support organizations, and standards setting organizations were invited and participated in the workshop by sharing a vast array of their experience and knowledge. In all, an accomplished mix of managers, project leaders, engineers and scientists from this diverse assemblage participated in the workshop.

The workshop was structured so as to provide basic background information related to the approach, state-of-the-art of inverters and power electronics, user requirements for inverters, DOE program requirements for inverters, inverter design issues, existing manufacturing research programs for inverters and finally university perspectives on inverter research. Breakout sessions followed the basic background overview. The breakout sessions were divided into two main focus groups. Group 1 focused on **"High Reliability Inverter Requirements"** and Group 2 focused on **"Low Cost Inverter Requirements."** The contrasting high reliability and low cost focus was chosen because they represent targets that are in opposition until a product is mass-produced. There were two sessions that then called upon each of these two focus groups to form consensus based on the low cost or high reliability end goal. The first was **"WHAT IS NEEDED?"** and the second was **"WHERE TO GO FROM HERE."** Each of the breakout sessions concluded with a breakout interim report from each group. The breakout sessions were summarized and presented as "Final Group Reports". The final reports were then followed by lively and productive discussion periods.

A primary goal of the workshop was to acquire DOE program and R&D directions from experts associated with the manufacture of or the need for inverters. To meet this goal, each speaker was requested to include the status, market, future, issues, requirements, as well as other constraints for inverter hardware or applications in each presentation. An overview of the critical points made in the presentations is included in Section 9 of this report.

A summary of the inverter related input gathered from the presentations and breakout groups is included in Section 10 of this report. This summary reports that the workshop participants considered higher reliability the most important aspect of inverter needs and development today. Lower cost was observed as very high in priority, but it often came with caveats that reliability was more important or that lower cost is not needed immediately. Other notable inverter needs for the high reliability focus included reliable utility interface, transparent (customer doesn't know it is there), smart (plug and play), improved packaging, communications (primarily customer), self protection, modularity, improved passive components (capacitors and magnetics) reliable switch gear, quality control, and advanced control algorithms. Other notable priority needs with a low cost focus included plug and play (especially for residential), improved applications (for schools, new construction and utility scale), low life-cycle costs, lower maintenance, standardization (performance reporting, human interface and communications), capacitors (energy storage), thermal management, improved physical packaging, and better control algorithms.

After hearing all the presentations, it was obvious that there are currently several excellent DOE-funded inverter development efforts, and a tremendous cache of knowledge exists within the individual development programs. Judging from the level of enthusiasm and individual participation at this workshop it was also obvious that there are many researchers that are eager to know what is going on in other programs. Many saw opportunities for collaboration that could reduce duplication of effort and allow more focused research in each area. A general observation was "At hand are obvious and "Tremendous Opportunities for Collaboration" among the DOE programs and the research and manufacturing facilities for inverter R&D." One recommendation that arose from the workshop was the suggestion that regular inverter workshops could establish valuable communication links and help set up collaborative efforts among the researchers and the DOE programs. This also would fulfill the communication and collaboration needs that must be included in a "DOE 5-year Inverter Research and Development Plan."

The discussions and consensus established in the breakout group sessions contained a valuable package of information on the status, markets, needs, directions, and future visions for inverters for all applications. The package contained a set of disparate suggestions and topics but also contained a compact set of needs and goals for the future inverter research and development. Results of the breakout sessions pointed to **higher reliability** as the "Number One Need" for inverters in the short term. Lower inverter costs were ranked high, but always rated lower than reliability in all but one category, namely utility-scale applications. The utility application experiences for inverters (represented at the workshop) have been very positive with 99% availability from inverters in distributed generation systems. That background resulted in a different set of priorities for the inverters for utility applications where the need to establish a reliability database was considered the most important.

Other significant recommendations emerging from the workshop included a need to establish a "DOE 5-year Inverter Research and Development Plan" followed by a program to improve inverters for all distributed energy (synergistic) applications. Cross-technology efforts from the inverter designers, manufacturers, user technologies, and DOE programs were recommended in several areas. The "DOE 5-year Inverter Research and Development Plan" will be written to include key participants from all facets of inverter technologies with strong coordination to assure key researchers from academia, industry, national laboratories, and program administrators are integrated. One recommendation for the methodology for establishing a systems-driven approach for a DOE inverter development program included tying it to a systems-driven approach solar program. It was recommended that an ADVISOR-type model for the solar program should look at the field of inverter manufacturers and users and decide if it would pay to integrate early and adapt other models. The benefits of early integration could be shorter design times and improved designs. Some of the issues suggested included: 1) the need for determination of "*the boundaries of the inverter (exactly what is an inverter) and 2) at what point do companies decide they need to use modeling tools?*

The need to develop key components such as capacitors or improved magnetics for inverters was identified as a critical need for inverters for solar, photovoltaic, energy storage, transportation and DER, but it could not be established that DOE programs, such as solar, should fund the development of these components. There was a unanimous agreement that the inverters used in solar, distributed resources or energy storage would not drive the development of power semiconductors, but a synergism with a very large market such as automobiles, motor drives or power supplies could help attract newer and improved devices into the smaller market of distributed energy inverters.

2 Introduction

The United States Department of Energy, Solar Energy Technologies Program led a two-day workshop to discuss a “Systems-driven Approach” to inverter research and development on April 23-24, 2003 at the Maritime Institute in Linthicum, MD. This workshop was a follow-up to the DOE Systems-driven Approach Workshop to Solar Energy held in December 2002, and focused on the inverter aspects of the approach to the DOE Solar Energy Technologies Program. The invited participants explored how the approach can help define the research and development needs and the technology requirements for a new generation of inverters for solar energy, energy storage, transportation, and distributed generation. Issues of common interest with all solar energy, energy storage, transportation, and distributed energy applications were explored. Similarities in the methodologies for the development of a new generation of inverters for all workshop related applications were discussed as was key tradeoffs such as low cost versus high reliability, long life versus throw away and modular versus custom packages.

The workshop was structured so as to first provide an overview of key information related to the approach, state-of-the-art of inverters and power electronics, user requirements for inverters, DOE program requirements for inverters, inverter design issues, existing manufacturing research programs for inverters and finally university perspectives on inverter research. Each category of information exchange was followed with a participant discussion period.

Focused breakout sessions followed the background information review. The breakout sessions were divided into two groups. Group 1 was focused on **“High Reliability Inverter Requirements”** and Group 2 focused on **“Low Cost Inverter Requirements.”** Two breakout sessions used these two groups. The first was **“WHAT IS NEEDED?”** and the second was **“WHERE TO GO FROM HERE.”** Each of the breakout sessions concluded with a breakout interim report from each group. The workshop facilitators from McNeil Technologies summarized and presented the “Final Group Reports”. The final reports were then followed by lively and productive discussion periods. Figure 2.1 shows the flow of activities used in the workshop.

Dr. Raymond Sutula, Program Manager for the Solar Energy Technologies Department, kicked off the workshop with a presentation that provided an overview of the framework of the approach and the benefits of the approach. He then challenged the workshop participants to explore the current markets, synergistic characteristics, the cost drivers, the reliability issues and finally what changes are needed to significantly improve inverter performance and reliability. The tasks for the workshop participants were set with a call for a workshop consensus on the expectations and targets for what a can or should deliver for inverter research and development, a basic framework for a “5-year Plan for

Inverter Research and Development" and a schedule for starting the process and creating near-term, mid-term and final deliverables for PV and other distributed energy resources. The "Systems-driven Approach" overview was complemented by a National Renewable Energies Laboratory (NREL) "Vehicle Technologies Model Demonstration" presentation. The "Vehicle Technologies Model" has been used extensively in the approach used in the DOE Automotive Development Program. The general activities of the workshop then turned to background presentations by Sandia National Laboratories' engineers that appraised the state-of-the-art for inverters, power electronic devices and switching technologies.

One of the primary goals of the workshop was to solicit directions from experts in each of the energy delivery technologies that need inverters to complete the power delivery system. To accommodate this goal, the objective of the workshop presentations then proceeded to examining the specific needs of each facet and finding the common needs for the program. The invited speakers included industry representatives from photovoltaics, transportation (electric vehicles), energy storage (batteries), fuel cells, and micro-turbines. Each technology speaker was asked to report on the status, market, future, issues, requirements, as well as other constraints as detailed in Section 9 of this report.

Another critical facet in examining the status of inverter developments, needs, and future requirements was the viewpoints and directions of today's DOE programs for solar, renewable, distribute resources and energy storage. Speakers from the DOE Office of Solar Energy Technologies, the Office Distributed Energy Resources, the Energy Storage (Office of Electric Transmission and Distribution), the Small Business Innovative Research and the Office of FreedomCAR and the Vehicle Technologies Programs were invited to speak. The presenters in this category were asked to report on the status, the budgets, the needs, and the plans for inverter work in each program and provide an overview of the scope-of-work.

Inverter-specific design issues associated with components, packaging, external requirements, mode-of-operation, operating characteristics and manufacturing processes were reviewed by experts from Oak Ridge National Laboratory and the NREL. These presentations were followed with a presentation that provided one university perspective, via Virginia Tech, on inverter development issues.

The amalgamation of workshop presentations provided an excellent overview of the status of the inverter situation and also highlighted factors influencing efficiency, reliability, cost, maintenance, manufacturability, and cross-technology applications. All of the presentations combined to bring to light the potential R&D targets and tradeoffs for future inverter developments.

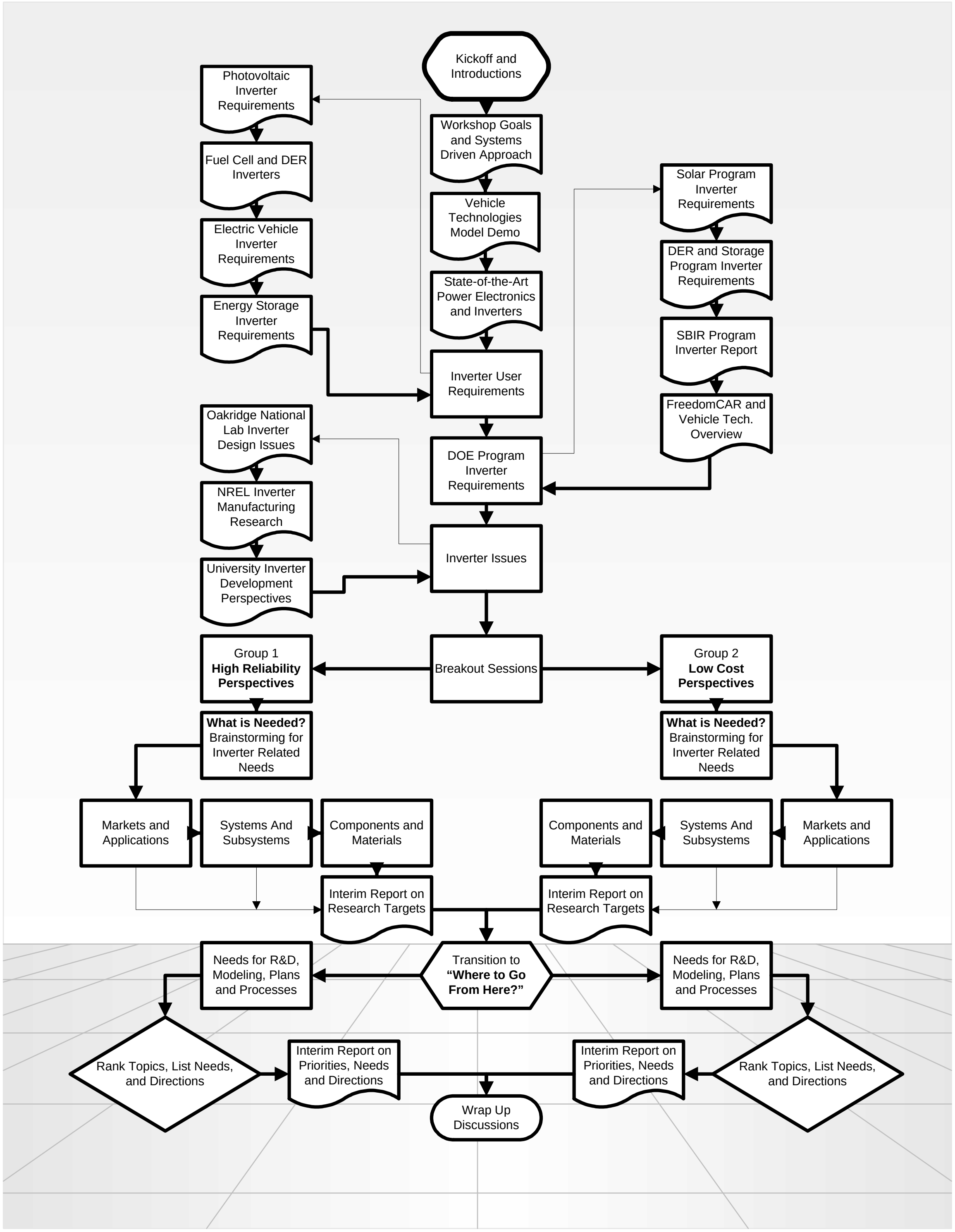


Figure 2.1. Flow of Activities for the DOE Workshop for a Systems-driven Approach to Inverter Research and Development

3 Workshop Goals and Targets

3.1 Goals

There were two main goals targeted in this workshop. The first was to apply a systems-driven approach to define the requirements for a new generation of inverters for all renewable and distributed energy applications. The inverter performance and cost goals specifically included:

- *High Efficiency*
- *High Reliability*
- *Low Cost*
- *Low Maintenance*
- *Manufacturability*

A second but <u>major</u> goal of the workshop was to gather pertinent information to contribute to the development of a consensus-based "**5-year Plan for Inverter Research and Development"** to be led by the DOE Solar Energy Technologies Program.

3.2 Targets

A list of targets was distributed to all speakers and participants prior to the workshop. Some of the targets were chosen to present a challenge to the present state-of-the-art and some were reminders of requirements that are in place today, but that may change as the technologies advance. This list of targets was further supplemented with an extensive list of questions to be considered before arriving at the workshop. The list of questions with the feedback provided by workshop participants is contained in Appendix B.

- *30-year lifetime*
- *A dime-a-watt cost*
- *98% efficiency*
- *Code compliant*
- *Utility-interactive and stand-alone capabilities*
- *Plug and play for multiple applications*
- *Modularity as applicable*
- *Passive thermal management*
- *Recyclable*
- *Meets all environmental constraints (EMI, noise, interconnection, thermal, safety)*

4 Workshop Participants

Key participants from the inverter industry, the distributed energy source industry, energy storage, transportation, system install organizations, universities, support organizations, and standards setting organizations were invited to participate in the workshop. Of note, more than 90% of the invitations were accepted. Several invitees requested that substitutes be invited in their place due to scheduling conflicts. A dozen other participants requested an opportunity to participate. In all, an excellent mix of managers, project leaders, engineers and scientists from this diverse assemblage attended the workshop. There were 64 participants and their contributions are incalculable. Each took valuable time from today's hectic schedules and shared a vast range of experience and knowledge with other participants. Thanks to the efforts of all, every workshop contributor went away with much more knowledge than they brought. Figure 4.1 is a pie chart showing the principal affiliations of the workshop participants.

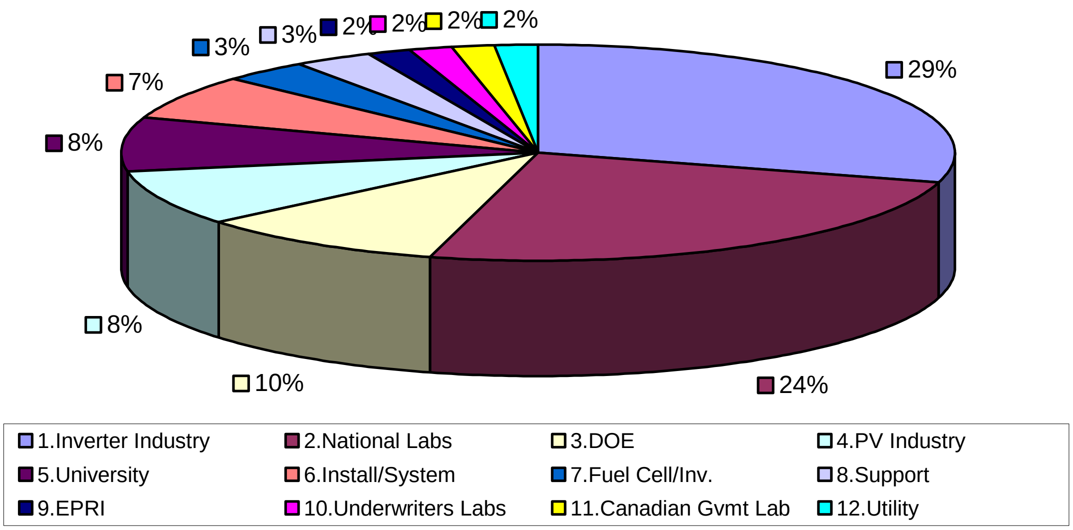


Figure 4.1. Pie-chart Showing Approximate Mix of Support and Participants for the Systems Driven Approach to Inverter Research and Development

Note that many of the participants actually represented more than one category and that the supporting affiliation is listed here. For instance, an engineer from an inverter manufacturer could also be serving on a standards committee and be engaged designing inverters for complete fuel cell applications. DOE representatives were typically managing some aspect of a program such as "Solar Technologies" or "Energy Storage" but their inverter work has recently included valuable cross cutting activities. For one last example, the fuel cell/inverter representatives represent a technology that critically depends upon an inverter for operation and may be involved in developing custom inverters, but are listed as a member of the energy source here if the fuel cell inverter is not independently designed and manufactured elsewhere. The complete list of participants, contact information and the primary affiliation of each is shown in Appendix A of this report.

5 Workshop Speakers

A list of workshop speakers, the title of each presentation and the order presented is shown below in Table 5.1. The complete set of slides used for the presentations is currently available upon request from McNeil Technologies or Sandia National Laboratories. It is as an attachment CD on the back cover of this report. Call or email Ward Bower at 505-844-5206 (wibower@sandia.gov) for additional information.

Speaker	Title of Presentation
Dr. Raymond Sutula *US Department of Energy*	Systems Driven Approach to Inverter R&D
Mr. Terry Penny *NREL*	Improving Technology Development Through Systems Integration and Math Based Tools
Mr. Stan Atcitty / Mr. Ward Bower *Sandia National Laboratories*	Power Electronics Converters: Technology Features, Markets.
Mr. Michael Johnston *AstroPower, Inc.*	Photovoltaic Inverter Needs
Mr. Jon Lutz *UQM Technologies*	Electric Vehicle Inverters
Mr. Fred Flett *Ballard Power Systems*	IPT Electronics – High Power Density Inverter
Mr. Ray Hudson *Xantrex Technology, Inc.*	Energy Storage Inverter
Mr. Dan Ton *US Department of Energy*	DOE Solar Energy Technologies Program - Inverter R&D
Dr. Imre Gyuk *US Department of Energy*	Energy Storage, A Market for Power Electronics
Mr. Paul Duncan *Airak, Inc.*	Update on Optically Interconnected Inverter System
Mr. Bill Kramer *NREL*	Office of FreedomCAR and Vehicle Technologies Advanced Power Electronics Overview
Mr. Don Adams *Oak Ridge National Laboratory*	ORNL Power Electronics Research for DER Utility Interfaces
Mr. Dave Mooney *NREL*	PV Manufacturing R&D – Inverter Manufacturing Progress
Dr. Dushan Boroyevich *Center for Power Electronics Systems; Virginia Tech*	Power Electronic Converters for Advanced Electric Power Systems

Table 5.1. Presenters for the DOE Workshop for a Systems-driven Approach to Inverter Research and Development

6 Workshop Facilitation

The staff at McNeil Technologies of Springfield, VA worked closely with the workshop planning committee for this DOE Workshop on Systems Driven Approach To Inverter Research & Development. The planning committee consisted of Kevin Degroat and Irrsula Mpouma of McNeil Technologies, Raymond Sutula, Dan Ton, and Alec Bulawka of the DOE Solar Energy Technologies Program, Ward Bower, Paul Klimas and Craig Tyner of Sandia National Laboratories, and Larry Kazmerski and Roland Holstrum of NREL.

McNeil Technologies facilitated the workshop and provided for the meeting facilities at the Maritime Institute in Linthicum, MD. Kevin Degroat and Dennis Fargo of McNeil led all of the technical sessions, the meeting discussions, questions and answer periods, break out sessions and finally presented the final summary reports. Ms. Irrsula Mpouma provided the critical meeting logistics, collected and assembled all presentations, contacted speakers, made available the workshop handout materials, agendas, and the list of participants, and posted participant notes and answers to pre-workshop questions.

Thanks to the McNeil team and the planning committee for organizing and completing this very successful workshop.

7 Workshop Organization

7.1 The Workshop Presentation Background

The workshop was organized so as to flow from initially providing critical background information to a very diverse audience and then moved forward to organized breakout sessions where critical needs and requirements information were collected. The material in the presentations flowed from an overview of critical foundation information related to the approach, state-of-the-art of inverters and power electronics, user requirements for inverters, DOE program requirements for inverters, inverter design issues, existing manufacturing research programs for inverters and finally university perspectives on inverter research as shown in Figure 2.1. The detailed agenda for the workshop is attached as Appendix C. Speakers were asked to follow a specified presentation format and to report on a given set of information.

Each **"industry**" speaker was asked to provide answers or issues related to the following:

1. *What are the inverter requirements unique to each application or technology including,*
   a. *What is the status?*
   b. *What is the market?*
   c. *What is the future?*
   d. *What is the probability of successful market?*
   e. *Is there enough market to drive down inverter costs?*
2. *What are the cost-related issues and inverter requirements?*
   a. *How many can be sold?*
   b. *Is there a reasonable fraction of overall system costs that inverters need to meet? Half of system costs? One third?*
   c. *Is this application is first cost an issue? If so, what are the constraints?*
   d. *Is levelized cost an issue? What should the inverter's share of levelized cost be?*
3. *What are the performance issues?*
   a. *What are the allowable standby losses?*
   b. *What startup and shutdown characteristics are needed?*
   c. *What transient responses are expected?*
   d. *How does efficiency versus costs versus reliability affect the inverter requirements?*
4. *What are your electrical/mechanical requirements?*
   a. *What are the sensitivities to power quality?*
   b. *Is there a need for utility-interactive or stand-alone?*
   c. *What are the sensitivities to lightning, heat, and environmental conditions?*

d. *What is the range of inverter capacities (continuous, surge, overload)?*
e. *What are the dimension criteria – size and weight?*
f. *Is communications required and is it local or remote?*
g. *How much reliability is required? How to measure it? Is degradation acceptable? What MTBF (mean-time-before-failure) is needed? What is the expected overall lifetime?*
h. *Can reliability trade off with cost?*

5. *What is missing from today's inverters? (This prioritized list was also referred to during the breakout sessions)*

Each of the **"DOE program"** speakers was asked to tailor his or her presentation to include the following:

1) *Provide a description of the program being presented*
   a) *What is the scope?*
   b) *What is the status?*
   c) *What are the needs?*
2) *What is the program budget?*
   a) *Describe the overall, near-term, long-term (5-year) plans*
   b) *What are the major categories of investment?*
   c) *Which labs and principal investigators are involved?*
3) *What are the program's major milestones and plans?*
4) *What are some of the major accomplishments of the program?*
5) *Who is the industry and how does it fit in the program?*
6) *How does this program fit with the rest of the DOE Energy, Efficiency and Renewable Energy (EERE) Department?*
   a) *Where is the collaboration?*
   b) *Where should there be collaboration?*
   c) *What would you do differently if you had other programs?*
   d) Is duplication of effort an issue?

7.2 The Workshop Presentations Overview

The flow of the presentation sessions was designed to first establish a baseline understanding of the approach to inverter research and development as shown in Figure 2.1. Dr. Raymond Sutula, Program Manager of the DOE Solar Energy Technologies Program, presented an overview of the systems-driven approach that included the framework and benefits. He then challenged the workshop participants to explore the current markets, synergistic characteristics, the cost drivers, the reliability issues and finally what changes are needed to significantly improve inverter performance and reliability. Figure 7.1 depicts the general framework of the approach with the systems associated with the end market having a significant influence as to what research is needed. A task for the workshop participants was set with a call for consensus on the expectations for what such an approach can or should deliver. The deliverables were needs for inverter research and development, a basic framework for a "5-year Plan for

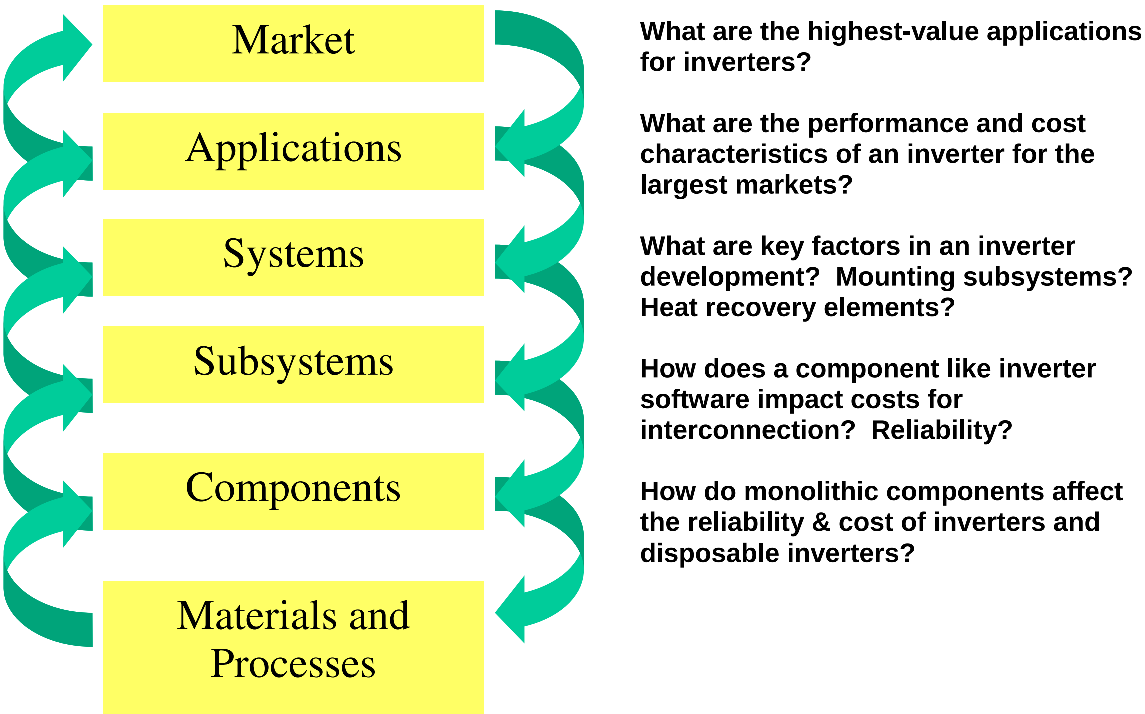


Figure 7.1. Diagram to illustrate the "Systems Driven Approach" Analysis Framework Progressing From Market Needs To R&D Programs With Appropriate Feedback To The Market.

Inverter R&D" and a schedule for starting the process and creating near-term, mid-term and final goals for photovoltaics and other distributed energy resources.

Mr. Terry Penny followed and complemented the concept through his "Vehicle Technologies Model Demonstration" presentation. The Vehicle Technologies Model has been used extensively in the systems-driven approach in the DOE Automotive Development Program.

The focus of the workshop then turned to examining the specific and common needs for inverter hardware in each of the DOE programs with presentations from DOE and National Laboratory personnel.

These presentations provided for examination of factors influencing efficiency, reliability, cost, maintenance, manufacturability, and cross-technology applications. Potential R&D targets and tradeoffs were addressed. All of the presentations are attached to this report on the CD located in the pocket on the back cover. A "5-year Plan for Inverter R&D" is expected as a spin off-product of this workshop.

7.3 The Workshop Breakout Sessions

Breakout sessions were the focus of the second day's work and followed the background review sessions. Both breakout sessions were given a long-term goal for the session. That long-term goal was to direct thoughts and actions to what is necessary to "provide ½ of the residential and commercial energy by the year 2050" through renewables. The breakout sessions were divided into two groups. Group 1 was focused on **"High Reliability Inverter Requirements"** and Group 2 focused on **"Low Cost Inverter Requirements."** There were two breakout sessions that used these two groups. The first session was **"WHAT IS NEEDED?"** and the second was **"WHERE TO GO FROM HERE."** The objective of the "What Is Needed?" session was to brainstorm all relevant topics and issues as a full group. Each of the breakout sessions concluded with a breakout interim report from each group. The "Where to Go From Here?" sessions further divided the teams into 5 sub-categories. The sub-categories were:

i. Residential
ii. Commercial
iii. Utility
iv. Off-grid
v. Village Power

The workshop facilitators from McNeil Technologies summarized and presented each of the "Final Group Reports". The final group reports were followed by a lively and productive full-group discussion session where suggested future tasks, modeling needs, additional questions and concerns and a parking lot list of topics not sufficiently covered in the workshop as well as how-to questions on defining the inverter, the mean-time-before-failure, and life-cycle costing. Section 10 of this report details the key findings.

8 Narrative of the Systems Driven Approach

8.1 What is the "Systems Driven Approach?"

All types of inverter technologies have many common challenges in entering markets and developing competitive applications, systems, and subsystems. Each approach also has its own unique positive attributes and specific technical challenges that need to be addressed through research and development. The U.S. Department of Energy's solar inverter research plans expect to focus resources and efforts on the most critical research challenges facing inverter development as a whole, regardless of whether the research focuses on solar technologies, non-renewable distributed energy technologies, energy storage technologies or research challenges that are common to all.

A broad perspective on inverter research and development is part of a renewed emphasis on the systems-driven approach to understanding the challenges facing all distributed energy sources and identifying the most important research required to create effective power transfer. As illustrated in Figure 7.1, the approach emphasizes the importance of how materials and processes, components, products, applications and markets for a technology are related to each other. It emphasizes how changes in a component such as an inverter might affect an application or market or how changes in a market might change requirements for component cost and performance (e.g., national interconnection standards could impact inverter design).

At the program level, this approach helps identify common elements that impact research and development. For example, all inverter technologies targeting residential generation for distributed generation share many similar assumptions about the interconnection to the utility, value of the system and the economics of owning the system. Applications integrated into building roofs or installed on roofs have common challenges in satisfying builder and owner preferences.

At the technology level, this approach can help identify common research concerns, avoid duplication of effort, and explore how advances in an area like subsystems might change the assumptions or requirements for systems, applications and markets. A systems-driven approach backed by modeling and analysis tools capable of illuminating systems issues provides a way to explore the implications of research goals and objectives in a systems context.

The DOE Solar Energy Technologies Program' strategy for conducting research, development, and related activities is focused on partnering with industry, academia, and other institutions to eliminate major technology-shortfall barriers – including related deficits in data, tools, or knowledge – that are retarding or preventing the practical application solar technologies and other distributed energy resources to meet present and future national energy needs. The approach will be employed to determine priorities for inverter research and development and for identifying key market sectors in which inverter improvements can have significant impacts. The approach is expected to help determine critical R&D to address technology barriers and develop standardized means of data collection and analysis to assure that fielded inverters meet targets related to cost, performance, and reliability.

By developing and using the approach, a standard configuration will enable rigorous target setting and decision-making. A computer-modeling platform will be developed to allow designers and users to conduct trade-off and impact studies of various inverter options within different market sectors.

Development of the modeling platform similar to that of the ADVISOR model now used by the Office of Advanced Automotive Technologies is needed. Technology baselines need to be documented in terms of cost and performance of inverters, with the goal of determining the overall costs of new inverter configurations and technology developments. Using this inverter "advisor" platform, analyses can be conducted in a manner that will include rigorous review by outside experts, and will be done at a level that will allow the identification of critical R&D efforts and the performance of appropriate cost/benefit/risk analyses of technology options under consideration. In this way, the systems-driven approach assures strong, direct linkages between the technologies developed for inverters and the national goals and markets for solar and other distributed energy resources.

8.2 What Is The Value of a "Systems-Driven Approach?"

A systems-driven approach, if applied correctly, offers clear advantages once market requirements are defined and understood. These include:

- By defining a clear set of market-based requirements and related system- and component-level technical targets, a systems-driven approach will allow project managers to more efficiently allocate limited resources to R&D efforts that yield the greatest impact on system cost and performance.
- A successful systems-driven program will provide researchers with tools to gain a much clearer understanding of the impacts of their specific R&D options on overall system cost and performance.
- Data generated from a well-managed approach will provide the Solar Energy Technologies Program with a more credible and defendable story regarding the impact of R&D efforts on DOE and National goals.

8.3 How a Systems-Driven Approach Will Be Used in Solar Energy Technologies Programs

Within the Solar Energy Technologies Programs, the systems driven approach to inverter R&D can be used to:

- Align inverter development efforts and objectives with market-specific requirements (i.e. requirements for grid-connected distributed, grid-connect utility-scale, residential, commercial, remote, etc.)
- Apply a consistent methodology in the development and use of analytical tools to analyze the impact of inverter R&D endeavors (improvements in cost, performance, and reliability) and non-R&D activities (learning curve, economies of scale, financing, policy) on the costs and impacts of the Solar Energy Technologies Program.
- Develop and document a consistent methodology for continuously updating information on the cost, performance, and reliability of inverter technologies under development and fielded through the program.
- Assess the relative probabilities of success among different technology R&D options, allowing informed decision-making at all levels.

8.4 The Systems-driven Approach Applied to a 5-year Plan

The inverter industry, for many applications involving renewable energy, distributed generation, energy storage, or transportation, has not fully matured and is undergoing rapid evolution as new devices and technologies are being integrated into a wide range of products. The industry would most likely be further advanced if a systems-driven approach had been applied to research and development in a consistent manner. However, it is not too late. Market- and system-driven goals could be implemented in the nation's national laboratories, university research and industries designs to sharpen the focus of today's development of inverters where near- and mid-term needs from the consumer industries are calling for low cost, high performance, flexible and consumer friendly inverter products.

Integrating the systems-driven approach into a 5-year research and development plan for inverters would establish a long-term and consistent schedule of activities to meet all of the values and implementation strategies discussed above. A DOE 5-year plan for inverter R&D is one of the key goals of this workshop and it is intended to apply the systems-driven approach and to use the results of this workshop.

9 The Workshop Presentations

This section contains an overview of each presentation given at the "DOE Workshop on a Systems-driven Approach to Inverter R&D." This section also attempts to point out specific needs and commonalities in the needs for inverter R&D as disclosed in each presentation. The commonalities and issues are narrated in each section, and are then collected in the tables that follow in Section 10. All of the slides presented at the workshop are included on the attached CD located in the pocket inside the back cover of this report.

9.1 The Systems-driven Approach to Inverter R&D

Dr. Raymond Sutula, Program Manager of the DOE Solar Energy Technologies Program provided the opening workshop presentation with a "Systems-driven Approach" presentation with an objective of developing the requirements and specifications for a solar systems framework that will allow exploration of alternative pathways and identification of critical technology needs that guide planning and management. He used the example of the "Advanced Vehicle Simulator" (ADVISOR) and its capabilities for code processing for product development, automation for product design and analysis, and abilities to draw roadmaps. He also identified the benefits of the ADVISOR modeling capabilities. Those benefits allow concurrent product development, reduce learning curve times for advanced technology, provide higher quality end product, allows for modeling of technology targets.

Ray used the "Approach" framework for analysis shown in Figure 7.1 to illustrate the pathways provided by the methodology. He provided examples of some of the possible inputs and outputs along with the direct and indirect benefits. Some of the direct benefits include the establishment of credible models for key markets and applications, documentation of consistent methodologies, analysis (in terms of energy contribution, carbon displacement, oil displacement, and energy security/reliability), and the creation of a process to strengthen the programs rationale for energy and to guide R&D efforts.

Some of the important indirect benefits included prioritization of R&D, alignment of technology development with objectives, comparative cost and performance methodologies, and a method to collaborate with experts and senior researchers through an established communications link within the model.

Ray challenged the workshop participants with key questions related to inverters and the three partitioned subjects important to a systems-driven approach to inverter research and development. The three partitions consisted of (1) Markets and Applications, (2) Systems and Subsystems, and (3) Components and Materials that were applied in sessions throughout the workshop. A few of the key “Markets and Application” questions were:

- What markets are synergistic enough to use common inverter technologies?
- What is the inverter industry doing to address tomorrow’s markets?
- Can larger inverter market segments serve new developing applications or does this violate economic rules?
- What new markets are expected and how might these new markets affect future inverter designs?

A few of the key “System and Subsystem” questions were:

- What are reasonable cost, performance, reliability and lifetime goals for various components and subsystems?
- For what subsystems or components would it be most valuable to find new technological alternatives?
- What is a reasonable life expectancy of a system?
- Should complete system designs be pursued?

A few of the “Components and Materials” questions were

- Why a “5-year Plan for Inverter Development?”
- What should the “5-year plan” include?
- Is an inverter development effort needed?
- Should supporting components be developed?

Ray issued a final challenge by asking for consensus on what the approach can/should deliver, the basic framework and elements of the approach and schedules and next steps for starting the process and creating near-, mid-, and long-term deliverables. Refer to the CD attached to this report to view all of the slides.

9.2 Improving Technology Development Through Systems Integration and Math-based Tools

Terry Penney, Technology Manager of the FreedomCAR and Advanced Vehicle Program at the National Renewable Energy Laboratory provided an audience interactive presentation describing the systems-modeling approach for vehicle development and which complemented Ray Sutula’s Systems-driven Approach. He emphasized that the ADVISOR model should be thought of as a template for a systems-driven analysis and that it in fact had been adapted to address many different analysis and could be adapted to analyze inverter issues.

Some of the features and methodologies for ADVISOR include:

- ADVISOR is not one tool! It is the integration of many tools into a framework where the elements have a common link to the goals of the program.
- ADVISOR pulls in off-the-shelf models and data especially at the subcomponent level and relies on other models.
- ADVISOR has a model abstraction layer so there are different levels of effort and detail at each modeling step.
- ADVISOR includes a reusable workflow template that can be adapted to different issues. The SaberGuide is an example of a link in the workflow template.

Terry related the ADVISOR model to the solar program and suggested that in developing an ADVISOR for solar, the program should look at the field of inverter manufacturers and users and decide if it would pay to integrate early and adapt other models. The benefits of early integration could be shorter design times and improved designs. Some of the issues suggested by the participants include:

- *What are the boundaries of the inverter or (Exactly what is an inverter?) Is it everything on the inverter chassis, the entire power conversion system with disconnects and energy-flow monitors or just the controls and power switches.*
- *What are the boundaries of the inverter lifetime? Should our programs strive for 30-year lifetimes with higher initial costs or is a throw away design feasible?*
- *At what point do companies decide the need to use something like ADVISOR and how are the costs apportioned?*

As part of his interactive presentation, Terry also answered questions that dealt with terms such as six-sigma (one in a million failure rate), how the National Laboratories try to work with all businesses, large and small, how to work with problems that may be mechanical but often appear electrical and how to use sensitivity analysis to uncover the range of parameters involved and to determine exactly what is needed for inputs to the model. Many questions regarding the huge differences between a mature auto industry and a developing inverter industry were answered with examples including one showing how to find the noisy parameters that need immediate attention.

Terry explained the methodology for integration of math-based tools. His basic definition was "Integration of the latest Computer Aided Engineering (CAE) tools with advanced design techniques to solve key technical barriers and to accelerate the development process. Terry stated "we work closely with industry to identify technical challenges and provide innovative solutions." With this in mind, he then provided a sampling from the "NREL Tool Kit" for input into the ADVISOR. They included:

- TRIZ & Topology Optimization for conceptual design
- Parametric Behavioral Modeling CAD *(not dimension- but an attribute-driven design)*
- Finite Element Modeling (implicit, explicit, VPG)
- Multi-physics applications *(structural/thermal, fluid/thermal, electromagnetics, etc)*
- Optimization integrated with computer aided design (CAD) & finite element analysis (FEA)
- Design for 6-sigma using CAE (DFSS)
- Probabilistic Design Methods *(engineering quality into designs)*
- Experimental Design Techniques
- Integration with "Vehicle Systems Analysis" tools
- Engineering Resources and Computational Power available at the National Laboratories.

Terry used the following list of thought provoking examples to further illustrate the applications for models such as the ADVISOR.

- Overall Integrated Design Process
- Think Mobility Design Optimization (FORD)
- Robust Design of Fuel Cell Stack
- Power Electronics Cooling with Behavioral Modeling
- Design For Six-sigma in Battery Thermal Management
- Design of Experiments Techniques for Road Load Reduction
- Catalytic Converter

9.3 Overview of Converters, Power Electronics Status, Markets

Mr. Stan Atcitty and Mr. Ward Bower of Sandia National Laboratories' Energy Storage and Photovoltaic Systems R&D departments teamed to present an overview of inverter technologies, inverter requirements, the associated inverter features, and the major markets for today's inverters. The term converter was used throughout to include both ac to dc and dc to ac conversion. Converters require features such as control systems, thermal management, internal/external protection, and filters to help shape waveforms or to eliminate unwanted noise. The presentation also showed examples of basic components such as semiconductors. Figure 9.1 illustrates the complexity of technology features that must be considered in inverter designs.

Stan presented graphics showing the chronological advancements and evolution of power semiconductors used in inverters. He also showed and illustration of the capabilities of power semiconductors as shown in Figure 9.2. The research in new devices such as silicon carbide (SiC) was introduced along with the advantages and disadvantages of today's devices.

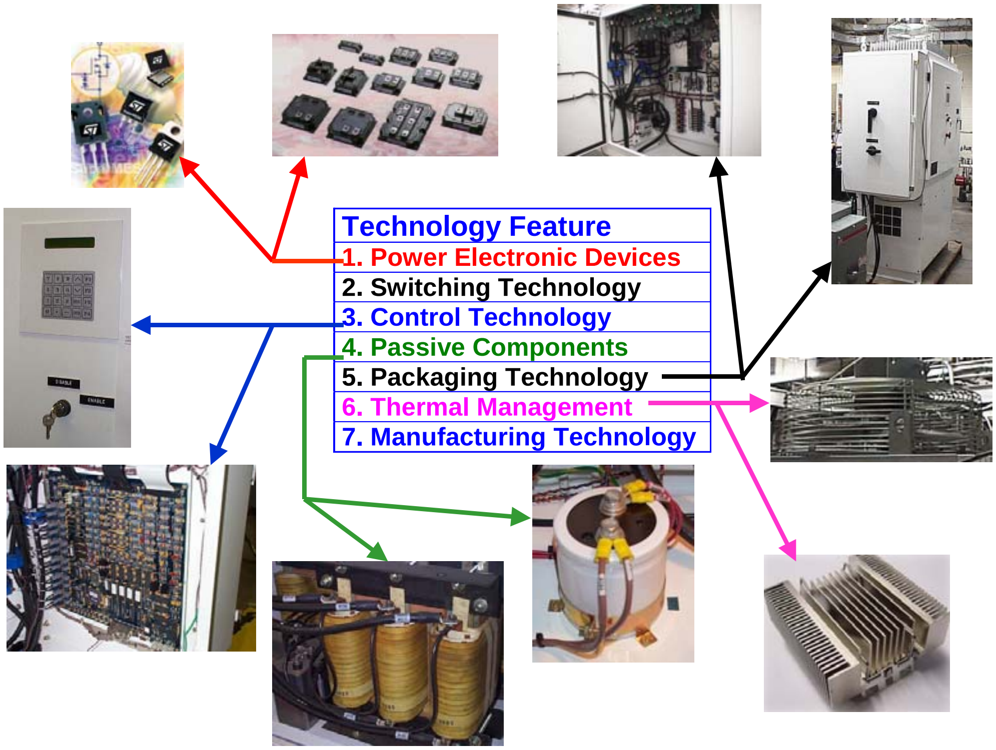
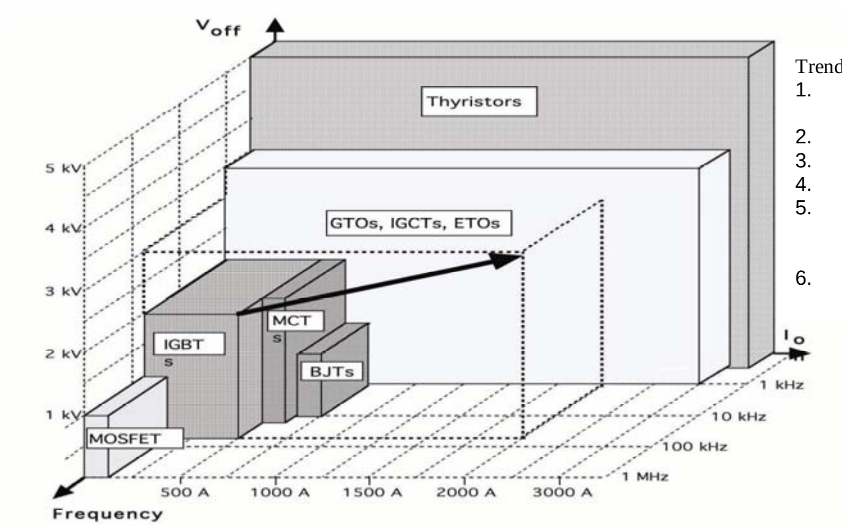


Figure 9.1. Illustration Showing The Technical Features Associated With Inverter Design And Manufacturing



Trends

1. Increase Voltage and Current ratings
2. Increase Switching Frequency
3. Lower Switching Losses
4. Improve Drivers
5. More Integration
    a. Self Protection
    b. Diagnostics
6. Lower Inductance

Figure 9.2. Range Power Semiconductors Available for Inverter Designers

He then assessed the “Low Power” electronic devices as on of the more mature technologies in power electronics. Even though a mature technology, rapid advances continue with resulting opportunities related to improvements in inverters.

Stan reported on the issues associated with today's inverter manufacturing. It concluded that:

- Most of today's inverters rely heavily on manual assembly
- The disparity in sizes and methods of interconnection increase the cost and reduce quality, flexibility, & reliability of inverters
- A good next step is a system-driven design approach using integrated packaging techniques and focused R&D.

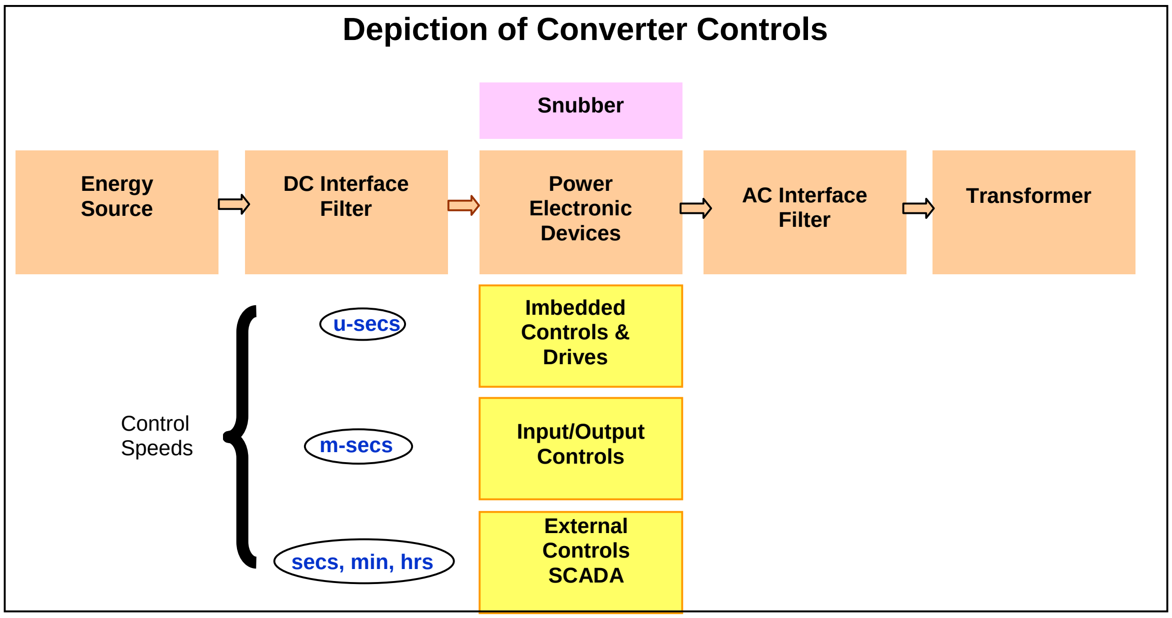


Figure 9.3. Block Diagram Depiction of Typical Inverter Control Loops Showing the Range of Speed Required

Major inverter markets were introduced, as was a perspective of relative market sizes. Major markets today are motor drives, power supplies and uninterruptible power supplies. Predictions for these markets indicate motor drives lead the market with $19.1B by 2005. Power supplies follow with $9.6B and uninterruptible power supplies with $5.2B by 2005. The total predicted market for the distributed resources including the combination of flywheels, fuel cells, micro-turbines, and solar was much smaller at $2.1B, but up from $0.4B in 2000. The predicted growth for the distributed resources was significant but must be tempered with the fact that inverters for these technologies differ significantly in topology, design, ratings and input/output criteria.

The cost of today's inverters was reviewed and it was reported that the inverter cost is often significant and ranging up to 25% of system costs. The average list price for inverters rated at 1-5 kW was reported to be $0.834 per watt. The average cost for a UPS inverter was reported to be $0.10/W. On the other end of the cost range, a stand-alone inverter cost of more than $1.20/W has been reported. It was also reported that inverter manufacturers are very reluctant to report costs.

Ward Bower presented an account of today's inverter issues and set the stage for the rest of the workshop technical activities. He reported there was little movement in the cost and reliability of inverters today because there is low remanufacturing volume for the renewable and distributed energy applications. Another key factor that requires careful consideration at least in the near term is the low profit margin associated with inverter sales. He listed what is needed to lead to the technical challenges facing the workshop participants and the industry. The list of what is needed includes:

- Reduce costs
- Improve reliability
- Develop state-of-the-art inverter with multiple uses
- Increase production volume through synergies in designs for many applications
- Improve controls and inverter adaptability
- Improve manufacturability

Ward introduced the technical challenges to be contemplated during the workshop. They included:

- Apply advanced technologies such as digital signal processors, advanced (made to order power electronics), advanced switching techniques and internal/external control methodologies
- Improve packaging and layouts
- Reduce thermal stresses through improved thermal management and reduced internal losses.

Today's and future institutional challenges included:

1. Develop multi-use designs to use synergism
2. Align with huge users and manufacturers to increase production volume and manufacturability
3. Require quality control in manufacturing including environmental and reliability testing
4. Provide FOCUSED Government-sponsored R&D
5. Provide manufacturing initiatives for existing and promising designs and hardware.

A key logistics challenge that must be considered for all new work include the fact that the demand for renewables and distributed energy sources **will not drive power electronics or silicon technology improvements!** Inverter designers and developers must also realize that standardization is possible, but custom design flexibility must be retained at least in the near future. Focused “Cross Technology” R&D can be a win-win for all technologies and inverter manufacturers.

9.4 Inverter User Requirements

9.4.1 Photovoltaic Inverter Needs (Michael Johnston)

Mr. Michael Johnson of AstroPower, Inc. provided a comprehensive overview of the inverter status, market, needs and issues for the photovoltaic industry. His inverter status report indicated there has been a recent shift to higher input voltage (up to 600V) for inverters, resulting in easier PV system installations. The inverter efficiency values are averaging between 89 and 94% and inverters now include maximum power point tracking as a standard feature. The single unit cost is ranging from $0.60 - $1.00/W.

Michael reported that on-grid applications without a uninterruptible power supply (UPS) is driving the domestic PV market growth and is currently 95% of the photovoltaic residential business. The residential systems range from 1.6 – 9.6 kW with the most common sizes being 2.4, 3.6, 4.8, and 7.2 kW. A wide variety of commercial system sizes ranging from 10 – 300 kW are being installed.

Michael then presented an extensive list of “What We Want From Tomorrow’s Inverters” for the PV industry. A summary of the basic needs that were key to the workshop topics included:

- Both utility-interactive and stand-alone capabilities
- Efficiencies in the 94% range with a flat load curve
- Life expectancy comparable to PV modules (25 years)
- Mean time before failure (10 years)
- Low infancy failure rates (<1%) bettering today’s >5%
- Extensive local communications for diagnostics
- No fan or thermal de-rate
- Smaller and lighter (one person install)
- Low profile (minimize depth)
- Standard warranty > 5 years with optional 10-year
- Cost < $0.50/W

One of more provocative issues included introductions of whether a universal or modular inverter was the best choice to maximize flexibility. The needed range of input voltage was given as 48 – 600V with power ratings of 1-5 kW. He stated that an inverter with multiple string inputs (each with its own maximum power point tracker) would offer large advantages over what is available today for photovoltaic application. When addressing the reliability/cost trade off he saw little opportunity today, and reiterated that reliability is currently more important. The inverter cost currently comprises 10-20% of the system cost and is not priority number one for today's market.

Michael's summary slide indicated the PV industry needs "bullet proof" systems that feel like appliances in order to cross over into the mainstream residential consumer market. His final words on the order of priorities were:

1. Reliability
2. Flexibility
3. Cost
4. Efficiency

9.4.2 Electric Vehicle Inverter Technologies (Jon Lutz)

Mr. Jon Lutz of UQM Technologies provided a comprehensive overview of inverters for electric vehicles and other vehicle applications. The overview provided a status of the commercially available inverters and the range of applications in vehicles. The applications on conventional vehicles included inverters on ambulances, fire-fighting platforms, recreational vehicles, buses, boats and yachts. He went on to develop arguments that showed electrified vehicles open new, potentially high-volume markets for inverters.

Jon provided an operational comparison (voltage ranges and sizes) for inverters operating in vehicles (12-24 Vdc and < 6 kW) versus electrified vehicle inverters used to drive the vehicle. The drive inverters are typically high voltage inputs (up to 800Vdc) and have a broad range of power ratings (10-200 kW).

The vehicle inverter characteristics were listed. A new measurement method for inverter lifetime was introduced. He used the 10-year, 150,000-mile, 5000-hour vehicle component life requirements. One other critical factor was the inverter cost, which he labeled as the "Overriding Figure of Merit" for electrical vehicles. Other important characteristics needed for the electric vehicle inverter were:

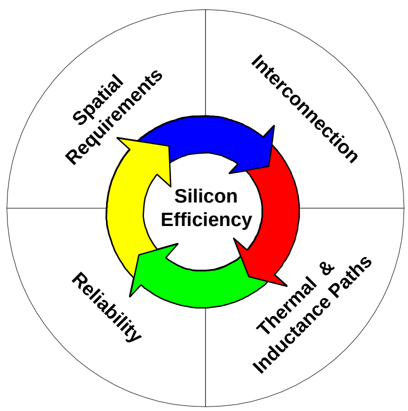
- Stand-alone (in most cases)
- High capacity (Continuous, surge and overload)
- Small and lightweight (1 – 2 kW/pound).
- Local and remote communications
- Low sensitivity to perturbations

Jon summarized what is missing from today's electric vehicle inverters as:

- Low cost ($0.06 to $0.10/W is required)
- Small size
- Ruggedness against vibration, shock and extreme temperatures
- Power capability
- Product availability for this developing market.

9.4.3 Integrated Power Systems (Fred Flett)

Mr. Fred Flett of Ballard Power Systems provided a spur-of-the-moment, although very well organized presentation to replace the scheduled presentation for the fuel cell industry. Fred's presentation provided a valuable overview of power semiconductor packaging advances, design and packaging, as well as opportunities for high power-density inverter design. The presentation added valuable up-to-date background materials and information to the semiconductor considerations for designing inverters of the future by discussing thermal stresses in wire bonds, inductive effects, thermal resistance predictions using numerical tools, and mechanical properties.



Other important advances presented by Fred included an example of inductance analysis for the dc link and electrical path inductance in the bond wires within the semiconductor package. He illustrated the benefits recently achieved in Ballard's inverter research and development programs. The benefits all are related to improved inverter performance and reliability and included:

- Increased package performance with significant reduction in parasitic inductance and thermal resistance allowing increased power density
- Increase packaging integration
- Reduced packaging space
- Reduced system cost
- Improved reliability

New power silicon trends and associated heat diffusion analysis was also presented. The trend to thinner wafers using trench rather than today's conventional planar technologies lead to improvements in the trade off of energy to turn the transistor off and the collector to emitter saturation voltage (both loss mechanisms). The trend and the characteristics are illustrated in Figure 9.4 and show a promising future for IGBT (insulated-gate bipolar transistor) devices.

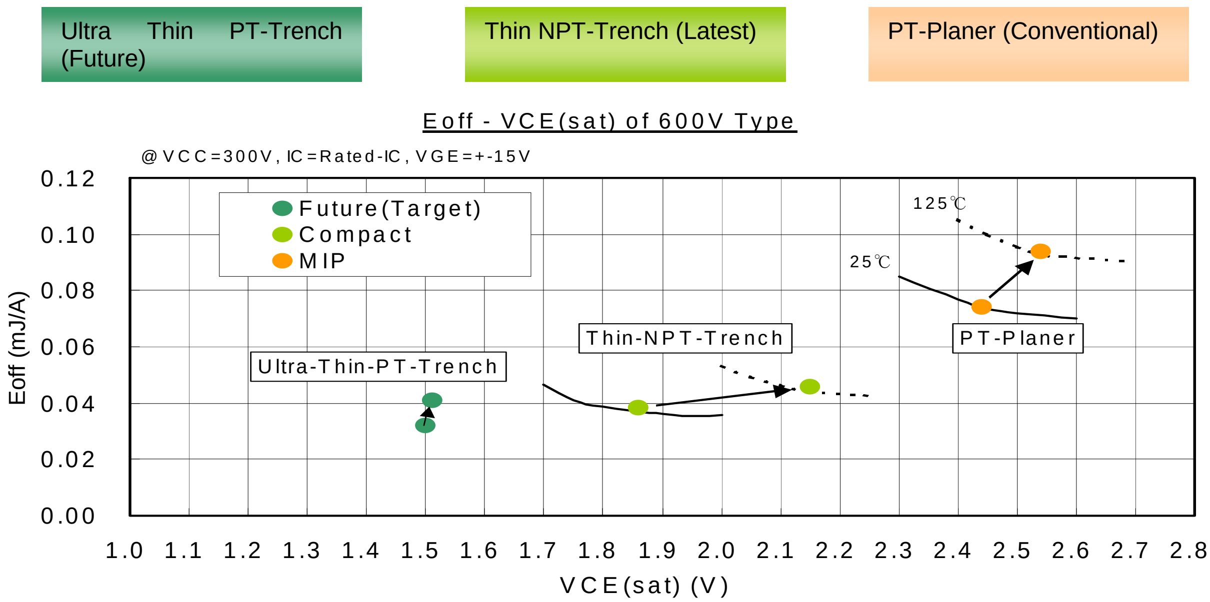


Figure 9.4 Dissipated Energy at Turn Off versus Saturation Voltage for IGBT Technologies

Fred continued his broad-based and informative presentation with an overview of power inverter hardware and analysis for a hybrid vehicle platform using a permanent magnet synchronous motor. He concluded with a list of further work that Ballard is conducting and needed for further inverter improvements. The future work list included:

1. Faster temperature sensing of the silicon junction
2. Silicon integration of the gate drive and sensing circuits
3. EMI (electromagnetic interference) containment through improved turn-on speed and diode recovery times and dc-bus capacitance integrated with the bus bar in the module.

9.4.4 Energy Storage Inverter Needs (Ray Hudson)

Mr. Ray Hudson of Xantrex Technologies presented an overview of the energy storage inverter issues. Inverters for energy storage span a broad range of applications from uninterruptible power supplies through very large mobile power through utility scale systems. With this wide variety of applications come a wide variety of load characteristics that in turn drive the inverter requirements from the load side. A wide variety of storage devices with vastly different characteristics drive the inverter requirements from the source side. Inverters often provide the charging controls and circuits for the energy storage.

The inverter for energy storage applications may provide short-term power such as in uninterruptible power supplies and for power quality improvement, or long-term power as in peak shaving and energy management applications. Inverters are sometimes tightly integrated and packaged with the energy storage device.

Ray reported mature energy storage batteries as including lead-acid, lithium-ion and nickel-cadmium. He also listed flow batteries (ZnBr, VRB, and PSB) as emerging technologies presenting different inverter/charger requirements. Other storage devices mentioned include flywheels, superconducting magnets, ultra-capacitors, fuel cells and mechanical storage such as compressed air or pumped hydro.

Ray then reviewed the market for energy storage device market as recording sales of $15B. The emerging device market is still small but growing. The demand for improved power quality and new opportunities for energy management offers good opportunities for the inverter manufacturers.

Ray provided a long list of challenges for the future inverter for energy storage. The list included:

- Lower cost per kW
- Higher reliability
- Higher efficiency
- Smaller size per kW
- Higher unit volumes
    - Comes from increasing demand
    - Improved through greater use of common modules
- Higher level of integration
    - Semiconductor devices
    - Control
    - Passive components
- Support for new and emerging storage technologies
- Transition from modified sine wave to sine wave for smaller systems
- Expanded communication features – standard protocols
- Failure prediction features
- Factory configured systems with generation and storage combined.

He then provided a discussion on the common electrical and mechanical characteristics of inverters used for energy storage. Many of the common desirable characteristics of the energy storage inverter were similar to those listed in previous presentations and included topics such as low sensitivity to line perturbations, a mix of utility-interactive and stand-alone applications, a wide range of power handling capacity, and non-typical surge requirements. He reported inverters should be physically smaller and lighter in the future. He said there was a need for both local and remote communications, and reliability to support the system warranties. The reliability and cost tradeoff of the inverter was mentioned as possible, but that reliability was an absolute requirement, and a market exists today for premium systems. Other features discussed was degradation over time with the conclusion that it is not acceptable for most applications, and that the typical customer wanted to install a system and then forget it.

The mean time before failure (MTBF) was also tied to the inverter supporting the warranty for the application. There are tremendous differences in energy storage applications where the inverter works continuously or those that are off-line and operate rarely. There are implications tied to the MTBF in both types of applications.

The issues associated with inverters today were categorized into performance, cost and markets. Ray called for inverter developments to support new storage technologies and with higher efficiency and higher reliability. The inverter cost curves continue to move downward, but he pointed out that the cost of the inverter was often a small part of the cost of a system. He ended the presentation with market comments that "the market and electricity reliability expectations are growing."

9.5 DOE Inverter R&D Programs

The next series of presentations focused on the DOE programs that require inverters. The series included solar technologies, energy storage, small business innovative research into storage inverters, FreedomCAR vehicle advances in power electronics, power electronics research and photovoltaic manufacturing research and development.

9.5.1 Solar Energy Technologies Program Inverter R&D (Dan Ton)

Mr. Dan Ton of the Solar Energy Technologies Program began this series of presentations with an overview of the Solar Energy Technologies Program inverter needs. He provided an historical summary of inverter activities and categorized them as past, present and future opportunities. He characterized the past with low reliability and high cost issues in a program had a different focus with low volume, customized designs with lots of discrete components coupled with inadequate quality control. Implementation barriers also added to the woes of grid-tied inverters for photovoltaic applications, as anti-islanding and operating limits were applied by the utilities.

Dan characterized the present as showing improving costs and quality of the inverter hardware and with a new system reliability emphasis. He emphasized that crosscutting with other distributed energy resource technologies would add to the reliability and quality of inverters through increased manufacturing volumes. He reported that quality improvements were being recorded as a result of highly accelerated life testing (HALT) and that standards are now reducing implementation and grid-tie barriers.

Dan offered that many future opportunities exist for the inverter designers and called for development of modular, multipurpose and plug-n-play designs. He also suggested all digital designs to add to flexibility and the use of crosscutting of the technologies to provide economies of scale.

He then reported on recent solar program inverter activities as very proactive with numerous efforts in interconnection standards, inverter certification and quality improvements through HALT evaluations. He revealed a 3-times improvement in MTFF through halt testing and new manufacturing programs for quality control and audits. Testing at Sandia National Laboratories through benchmarking of commercial products, development testing and special user requested testing has also been improving product quality and performance while reducing barriers to interconnecting to the utility grid.

He highlighted the recent "High Reliability Inverter Initiative" that has goals of:

- Greater than 10-year MTFF (2004 goal)
- Lower inverter costs
- Modular design for multiple technologies
    - *PV, Storage, Fuel Cell, DER*
- Flexible design for multiple applications
    - *Grid-tied, Stand-alone, Hybrid, UPS*)
- Scalable with < 10 kW initial size.

Future inverter research and development is now tied to the "High Reliability Inverter Initiative", but the outcome of this workshop, with a call for a "5-year Inverter Research and Development Plan" should be used in a systems-driven approach to determine the priorities for future R&D. Some of the topics mentioned for the future work included new modeling activities, manufacturing improvements, and thermal management. A focus on multiple application inverters was reiterated.

Dan also provided a recommendation for ties such as development of a plug-n-play modular inverter and the AC PV Building Block with collaboration with the automotive or other large industry ties that offer very large volume production advantages.

Dan concluded his presentation with a call for collaboration among the DOE program offices. He listed the following as possible collaboration parties in addition to the existing PV/DER/Storage collaboration.

- Office of Transmission and Distribution Reliability

- FreedomCAR and Vehicle Technologies Program
- Crosscutting in Monolithic Building Blocks, Plug-and-Play
- Technologies with Established High Volume (UPS, Motor Drives, etc.)

His final summons was that the DOE Solar Program was looking for opportunities to collaborate to:

- Develop a core/modular inverter program
- Push for an economies of scale
- Consolidate and focus resources
- Avoid "Re-invention of the Wheel!"

9.5.2 Energy Storage, A Market for Power Electronics (Imre Gyuk)

Dr. Imre Gyuk of the DOE Office of Electric Transmission and Distribution provided his perspective on inverters and power electronics. His initial slide declared "Power Electronics are Essential for Storage and DG Representing About 30% of System Cost." He went on to state the energy storage industry represent a multibillion dollar business and that energy storage mediates between variable sources and variable loads. He pointed out that the load variability results in low capacity factors and inefficient resource utilization that is currently 60%-70% for generation, 40%-50% for transmission and 35%-45% for the distribution levels. He then quoted an Electric Power Research Institute (EPRI) prediction that energy storage will increase the capacity for generation by 5%, for transmission by 10% and for the distribution by 15%. Imre reiterated the success of the energy storage impact depends crucially on improvements in inverter technology.

He then progressed to applications for energy storage that reside on both the customer and utility side of the energy supply. Table 9.1 shows the wide variations in applications for energy storage as related to load and grid requisites and the amount of time the inverter must operate.

	POWER Seconds	Minutes to Hours	**ENERGY** Diurnal
Load	Power Quality Digital Reliability	DER Support for Load-Following	Peak Shaving to Avoid Demand Charges
Grid	Voltage Support Transients	Dispatchability for Renewables, Village Power	Mitigation of Transmission Congestion/Arbitrage

Table 9.1. Applications for Energy Storage

Having illustrated the applications, Imre went on to verify the importance of reliability. He emphasized that high-tech demands 0.9999999999 reliability of the grid and that 98% of power quality events last less than 15 seconds, resulting in costs of $35B - $150B. He further expounded that only energy storage can provide the seamless continuity of the electric power supply.

Another important impact of energy storage will be relief of transmission congestion and possible arbitrage. Imre illustrated the benefits that can be derived from transmission deferral and further described examples of systems that are currently being used for voltage support, transient control and grid stability.

Peak shaving for profit and reliability was also illustrated. Imre reported that energy storage to ride out price peaks and to avoid peak demand charges amounted to a 460 GW potential market.

Making renewables dispatchable was reported as another important use for energy storage and the associated inverters. It could make wind farms dispatchable to bid on the spot market and increasing the value of the generated electricity.

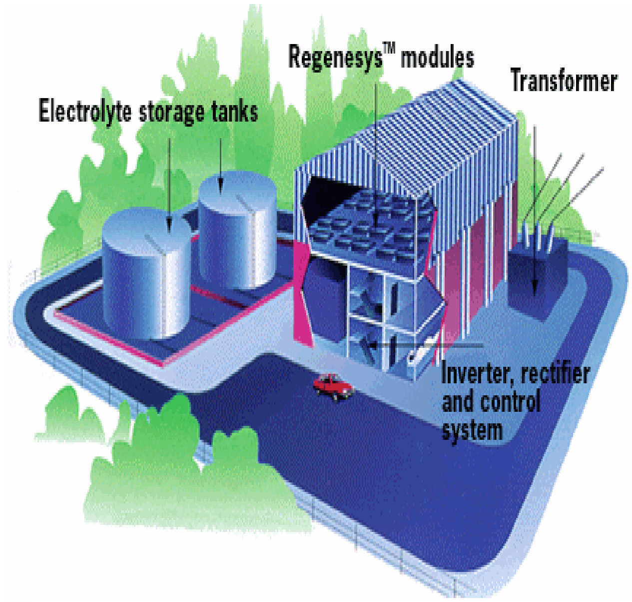


Figure 9.5. View of a 12-MW / 8-hour Flow Battery Facility

Village power was also reported as an important use for energy storage. The storage improves the efficiency and the reliability of a village grid. One-third o the world population is not connected to a utility grid.

Dr. Gyuk then switched to the DOE program goals for storage and the research underway. The primary DOE program goal is to develop a broad portfolio of storage technologies for a wide spectrum of applications. The DOE is currently supporting research on devices such as emitter turn-off (ETO) switches that were reported to be faster than a GTO (gate turn-off device), more powerful than an IGBT (insulated gate bipolar transistor) and less expensive. He reported that an ETO-based multilevel inverter has teamed with ultra-capacitors to maintain grid stability. He concluded his presentation with a slide that asserted that energy storage and distributed generation has huge economic potential but "IT WON'T HAPPEN WITHOUT BETTER INVERTERS."

9.5.3 <u>Update on Optically Interconnected Inverter System (Paul Duncan)</u>

Mr. Paul Duncan of Airak, Inc. provided the next presentation that covered material supported by a DOE Small Business Innovative Research (SBIR) grant. He reported on the primary project goals that were to *"Develop and test an advanced pre-production three-phase, 5-megawatt inverter system based upon*

HV-IGBT switches with complete optical isolation (control and sensing) between the high power subassemblies and the low power control and signal processing hardware." Secondary goals included a heat pipe thermal solution, the design of a system for manufacturability, completion of a system costing $150/kVA and with 99% efficiency, and optical current/voltage/temperature transducers for introduction into other electrical markets.

Paul reported the motivations for the project that were also a common theme for most of the preceding presentations. They included:

- There are few cost-effective, efficient power conversion topologies for high-power markets
- High-power conversion systems are largely based upon smaller conversion systems with applied scaling rules.
- There are no optically isolated interconnected high power systems in the market today.

He offered that his solution was optical sensor technologies plus high-voltage IGBT power systems plus advanced heat-pipe cooling solutions. He also offered some of the advantages that could apply to almost all inverter designs. The advantages of the high voltage power system and optical sensors included:

- Elimination of current snubbers and voltage clamps
- Simplified gate drive circuitry and isolation
- Higher frequency switching (~ 5 kHz)
- Intrinsic galvanic / electrical isolation
- EMI immunity => increased reliability
- Increased equipment and personnel safety.

The integrated heat-pipe cooling system offered the following advantages:

- Considerable life-cycle cost reduction over conventional pumping systems
- Lower (minimal) maintenance requirements
- Higher reliability
- Smaller footprint / compact design
- Degraded mode of operation possible
- Up to 20 kW of heat removal per phase leg.

Paul illustrated several packages developed under the current SBIR grant. One of those illustrations was a single-phase building block, but another was a 5-MW multilevel inverter showing a wide range of applications.

The anticipated markets for the developments under this grant are widely varied and range from emergency power markets, distributed energy markets, advanced power conversion (for fuel cell, flywheel, wind, hydro-turbine and solar), military markets and "all electric ship" applications.

9.5.4 FreedomCAR and Vehicle Technologies Advanced Power Electronics Overview (Bill Kramer)

Mr. Bill Kramer of NREL provided the next presentation and it was focused on the advanced power electronics development for the FreedomCAR and vehicle technologies program. The goals of the program were to *"Enable America to use less petroleum by researching and developing technologies to improve the energy efficiency of cars and trucks."* The imbedded advanced power electronics goals were stated as *"To develop power electronics and electronic machinery technologies that enable improvements in performance and dramatic decreases in vehicle system costs."*

Many of the reported barriers associated with the vehicle program were similar to other reports and included:

- Cost
- Volume
- Thermal management
- Weight
- Motor-inverter integration
- Reliability and ruggedness

The power electronic tasks associated with the vehicle program were reported to include:

- Develop improved inverter/converter architectures and topologies, including special bus-bar designs to allow faster switching and less expensive transistors
- Develop improved packaging concepts, focusing on integration of power switches, gate drives, control logic and filter capacitors to allow higher power density, higher reliability and lower cost
- Develop improved low-cost dielectric materials that increase capacitance for improved capacitors with high-temperature, high-current capabilities and low equivalent-series resistance
- Develop improved high-current sensors with high-temperature capabilities
- Develop efficient control algorithms and sensor-less control techniques
- Develop a semiconductor controller suitable for automotive use.

Bill detailed many of the tasks associated with development of the inverters for FreedomCAR and other vehicles. The motor/inverter integration focused on producing a single package capable of 15-year lifetime. The power electronics development focus was to reduce power electronics costs and improve performance and reliability through R&D. The capacitor development effort focused on low volume, high reliability capacitors that will reduce volume and weigh. High temperature polymer dielectric materials and high volume manufacturing processes will be developed. High-energy film capacitors are also being researched. A permanent magnet effort is focused on reducing the costs of materials and increasing the maximum operating temperature of electric drive motors. A motor-controller effort is focusing on a controller system on a chip to achieve cost reduction by integrating functions and external circuitry within the single device. Thermal management is being investigated with a focus to improve the thermal characteristics of power electronics. The objective is to find solutions that lower the cost, increase power density and increase reliability through innovative packaging, advance phase-change coolants, materials and new cooling techniques.

9.5.5 Oakridge National Laboratory Power Electronics Research for DER Utility Interfaces (Don Adams)

Mr. Don Adams of Oakridge National Laboratory provided an overview of the power electronics research for DER utility interfaces at the Power Electronics and Electric Machinery Research Center (PEEMRC). The PEEMRC is the US DOE broad-based power electronic and electric machinery research center that has advanced technology in multilevel inverters, soft-switched inverters, non-active power compensation, motor control techniques and efficient compact electric machines. Don described the national user facility at the PEEMRC and outlined the power electronics research areas. They were:

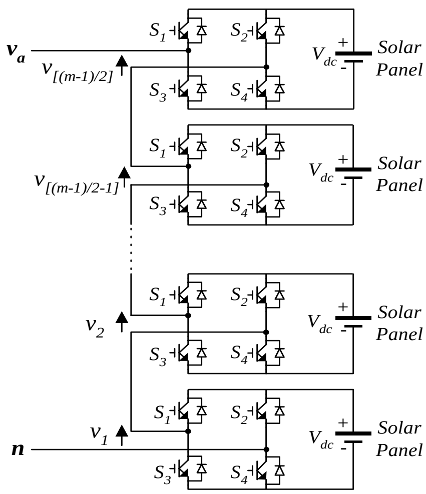
- Interface with distributed energy resources such as micro turbines, fuel cells, and solar cells
- Develop multilevel converters for utility applications such as static VAR compensation, voltage sag support, HVDC intertie, large variable speed drives
- Harmonics, power quality, and power filters
- Hybrid electric vehicle (HEV) applications such as motor drives or dc-dc converters
- Soft-switching inverters and dc-dc converters
- Application of wide-band gap power electronicsSimulation, modeling and analysis of power electronics for transportation and utility applications.

He then described the three-phase multilevel inverter that had been developed for solar energy as efficient with low switching losses, fault tolerant with automatic reconfiguration in events of faults, and able to achieve minimum total harmonic distortion even as the light intensity on the solar cells changes.
The multilevel inverter was described as able to:

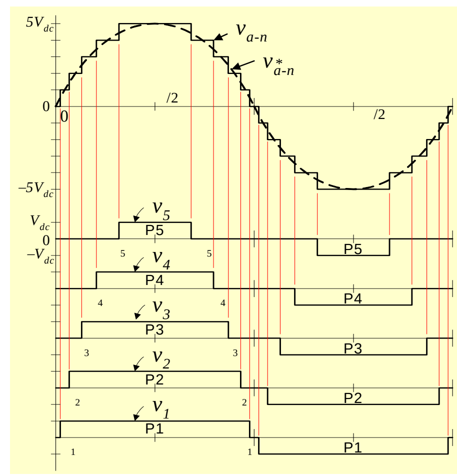
- Synthesize a sinusoidal voltage from several levels of dc voltages
- Use DC sources such as ultra-capacitors, solar cells, or batteries and can generate single-phase or three-phase output
- Utilize a fundamental frequency switching technique that yields very low switching losses and high converter efficiency

- Eliminate low frequency harmonics (5th, 7th, 11th and 13th) in the voltage output.

Figure 9.6 shows the power bridge configuration and typical waveforms for an 11-level inverter.



Single-phase m-level structure
V_{dc} is the output of a solar cell panel



Line-to-neutral Voltage for an 11-Level Inverter

Figure 9.6. Power Bridge Configuration and Typical Waveforms for an 11-level Inverter

In addition to solar applications, the multilevel converter has been considered for a wide variety of applications since 1993. Those applications include static VAR compensation, active power filter, voltage sag compensation, interface between DG sources and the utility, and medium voltage motor drives.

The advantages of the multilevel inverter were reported as:

- Modular with lower manufacturing costs
- Compact- no transformer needed
- None or reduced output filters
- Redundant levels for increased reliability
- Possible connections: single-phase, multi-phase, three-phase wye or delta
- Low switching frequency yields high efficiency
- Fundamental frequency switching
- Multilevel PVM

The power electronics research at the PEEMRC has been leveraged with transportation technologies for utility applications. Many of the utility application requirements for inverters exhibit similarities such as modularity, high efficiency, low cost, high reliability, control, bi-directional power flow, energy storage and minimized electromagnetic interference.

9.5.6 Inverter Manufacturing Research "Photovoltaic Manufacturing R&D" (Dave Mooney)

Mr. Dave Mooney of NREL provided a progress report of the PV manufacturing research and development program. The objectives of the program were stated as "*The U.S. DOE, working with the U.S. photovoltaic industry, initiated the PV Manufacturing R&D Project to conduct manufacturing research to accelerate PV production capacity scale-up and affect manufacturing cost reductions*." The program was initiated in 1990 and the total investment to date is approximately $140M where $80M was DOE share and $60M was industry share.

Dave reported that there have been 8 subcontracts involving inverter work since 1995 with $8.2M total contract values, with $5.4M being the DOE share, to date. He provided details on each of the inverter efforts with a summary of the manufacturers and project titles as shown in Table 9.2.

Subcontractor	***Title of Project***
Advanced Energy Systems	*Next-Generation Three-Phase Inverter*
Ascension Technologies	*Manufacture of an AC Photovoltaic Module*
Omnion Power System Engineering	*Three-Phase Power Conversion for Utility-Interconnected PV Applications*
Solar Design Associates	*The Development of Standardized, Low-Cost AC PV Systems*
Trace Engineering	*Modular Bi-Directional DC-to-AC Power Inverter Module for Photovoltaic Applications*
Ascension Technologies	*Cost Reduction and Manufacture for the SunSine 325 AC Module*
Omnion Power System Engineering	*Manufacturing and System Integration Improvements for 1- and 2-Kilowatt Residential PV Inverters*
Xantrex Technology, Inc.	*PV Inverter Products Manufacturing and Design Improvement for Cost Reduction and Performance Enhancements*

Table 9.2. Summary of PVMaT Subcontracts with Inverter-related Development.

These subcontracts all included goals of improving manufacturing of inverters, but also included many important goals for improved performance, integrating advanced technologies such as digital signal processing, soft switching or an integrated bus. Testing for safety and for improved reliability was conducted on most of newly developed hardware. Underwriters listing, ISO9001 quality assurance and compliance with other standards was also included as part of the subcontracts statement of work and deliverables.

Many advances were made in improved costs, reduced physical sizes, new circuit topologies, reduced parts counts, improved packaging, improved controls and reduced labor costs.

9.6 University Perspectives

9.6.1 <u>Perspectives on Inverter Developments (Dushan Boroyevich)</u>

Professor Dushan Boroyevich of the Center for Power Electronics Systems at Virginia Tech provided a comprehensive overview of source and grid-interface issues, modular converter design issues and standard-cell open-architecture electric power conversion systems. His presentation also provided a description of the Center for Power Electronics Systems as an industry consortium of 75 partners with five university partners. This consortium concentrates on research but is very active in outreach and education.

The center has been a partner in the Power Electronics Building Block and Advanced Electric Power Systems program conducted by the Office of Naval Research. A wide range of power electronic converters and motor drives have emerged out of that collaboration. A typical power electronics converter for renewable generation is shown in Figure 9.7 below.

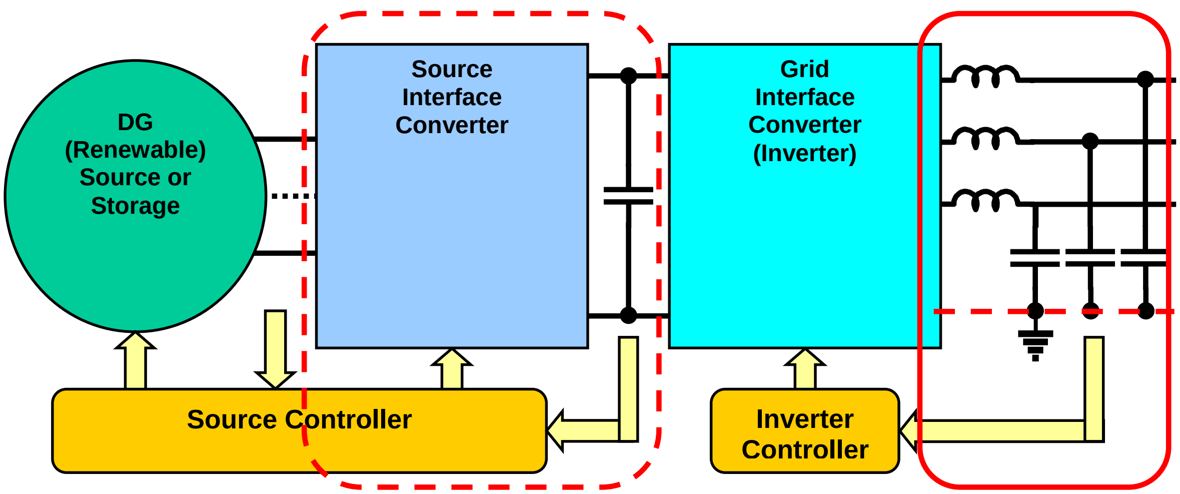


Figure 9.7. Renewable Energy Generation Configuration

Professor Boroyevich provided several examples of other generation configurations and at the same time began addressing critical characteristics that needed to be changed or improved. He concentrated on unbalanced/non-linear loads in many of his examples and showed the requirements for working with those loads. He also addressed switching noise of inverter systems and provided examples on how to reduce that noise through active common-mode noise elimination.

Several other examples of power conditioning systems were illustrated and detailed. Modular inverters with zero-volts, zero-current transition switching methodologies were presented along with several sets of waveforms showing the necessity of zero-sequence control with modular inverters. The modular "Plug & Play" control architecture was used as an example. He provided a set of three rules for connecting parallel inverters. They were:

- **Zero-sequence current** must be controlled in (*N*) parallel converters
- For modularity, you need independent controllers per converter
- New control algorithm provides for zero-sequence current control by:
    - A small modification in modulation
    - A simple additional (zero-sequence) current controller in *N*-1 converters

Professor Boroyevich's final slide provided a chart listing the basics for the conceptual reference model for the standard-cell, open-architecture, electric power conversion system.

9.7 Summary of Presentations Content

A broad and undeniable statement that stems from the content of the presentations given in this workshop is "At hand are obvious and <u>Tremendous Opportunities for Collaboration</u> among the DOE programs and the research and manufacturing facilities for inverter R&D." The collaboration would be a win-win situation for all involved and could apply a systems-driven approach to identify priorities and establish methodologies. The collaboration would conserve scarce DOE resources, speed development, enhance the knowledge of all, and very likely result in much better product for all consumers. The collaboration would eliminate much of the redundant efforts now underway, but would open the door for researchers to sharpen the focus to reach specific goals and in developing the ultimate state-of-the-art inverter hardware.

There were many common themes in the presentations. The most prevalent theme was a need for "**high reliability**" inverters. High reliability was followed closely by lower cost. It was noted repeatedly that both of these themes could be obtained through higher production volumes, standardized designs, improved manufacturing, modularization and incorporating larger scale integration and controls that are possible with digital signal processing and standardized modules of power semiconductors to provide the switching functions.

Coordination of the collaborative efforts could ensure that research facilities focused on critical elements in a well-planned R&D effort. It was suggested that an "Inverter Center of Excellence" be established where the coordination could be harmonized. A well-planned R&D effort must also be included in a multi-year plan for inverter R&D. A "DOE 5-year Plan for Inverter Research and Development" will be an outcome of this workshop.

The tables shown in 10.1a, 10.2a, and 10.3a provide a quick snapshot of the relevant inverter status, markets, needs and issues that were extracted from the industry presentations and subsequent discussions. Tables 10.1b, 10.2b and 10.3b the snapshot of the relevant inverter status, markets, needs and issues that were extracted from the DOE presentations and subsequent discussions.

Table 10.1a.	"Performance" Related Perspectives from Industry Presentations/Discussions			
Representation	**Status**	**Market**	**Needs**	**Issues**
Photovoltaics (Industry)	Currently shifting to higher operating (dc) voltages Efficiency Range is (89-94%) MPPT is Standard but some inverter MPPT are inaccurate. Thermal problems cause foldback in some inverters Inverters often need manufacturer adjustments when installed	On-grid, residential 1-9.6 kW On-grid commercial 10 – 300kW On-grid market has grown to become the majority market	Both U-I and S-A. 2.5 – 5 kW Residential. 10,30,50,100 kW Comm. Surge of 1.5 – 2X for UPS. 94% Average Efficiency (flat). Communications (local & remote). NO Fan/NO Thermal Derate. Smaller/lighter (1-person install) Modular inverter with: DC V = 48-600V Power = 1-5 kW.	Performance Lifetime 1. Reliability 2. Flexibility 3. Cost 4. Efficiency Universal or modular inverter needed.
Energy Storage and DER (Industry)-	Wide range of operating characteristics and sizes. Often integrated with the storage Wide range of performance and operating requirements. Often integrated into the resource (fuel cell, flow battery etc.)	Size range from small kW to 500kW May be high power short time or low power/high energy continuous Small is considered mature technology Mobile power Power ranges from <1kW to >200kW Market exists for both indoor and outdoor packages.	Emerging storage technology will require new inverter characteristics Lower Cost needed Higher efficiencies Smaller size/ kW Higher Mfg. Volumes Higher level of integration Communications \\ Modular Inverters Inverters that have a wide range of operating conditions.	Storage devices drive the inverter requirements from the dc side. Loads drive the inverter requirements from the ac side. Each technology presents a different set of requirements. Inverters must handle a wide range of operating conditions.
Electric Vehicle (Industry)	Inverters already available for specialty vehicles Existing inverters are 12-24V for less than 6kW used for low power applications. Inverters for electrified vehicles operate at 48-800V for 10-200kW.	Electric vehicles can open new higher volume opportunities. On road vehicles will provide 110 V outlets powered by inverters. Off-road vehicles will have inverters to power tools etc. (Include military, construction etc. Connected vehicles that interface with the grid. Hybrid vehicles coming.	Inverters for a variety of applications and interfaces. Rugged inverters needed. l	High capacity inverters for military applications. Fuel cell vehicles Connected cars that interface with the grid will need interconnect standards. Hybrid electric cars and trucks require new inverter technologies

Table 10.1b.	**“Performance” Related Perspectives from DOE Presentations/Discussions**			
Representation	**Status**	**Market**	**Needs**	**Issues**
Solar (photovoltaics) – (DOE)	High reliability inverter initiative begun in 2002 and continuing into Phase II. Also focuses on minimum efficiency, DSP controller and high power quality. Customized designs (or lack of standard designs) in the past resulted in reduction of inverter performance.	Solar market is demanding inverters that work as advertised. Inverter certification efforts have produced a draft test protocol for determining inverter performance. Grid-connected market becoming performance based	Standardized and modular designs to handle a wide variety of applications. Need versatile inverters with more than one dc input for alternative sources. Certification of inverters needed. UL or equivalent listing of inverters required	Anti-islanding issues have alerted utilities to listing requirements and inverter performance issues are needed Flexible and scalable designs allow for the wide range of PV applications.
Energy Storage and DER (DOE)	Wide range of custom inverters are available.\ AC battery available. New semiconductors being developed (Emitter turnoff transistors)	Market varies from small UPS to huge peak shaving energy production or power surge protection.	Dispatchablity required. Relief of electric transmission congestion via energy storage and inverter interfacing.	Village power also needed. Need better inverters. Need dispatchable inverters.
Transportation (DOE) **Note: FreedomCAR reference.)**	High-energy film capacitors being researched. High volume manufacturing being developed. Thermal management being investigated especially with the power electronics sections	Thermal management is required before entering into the market.	New semiconductors needed. Controllers suitable for automotive use needed.	Need improve inverter architectures and topologies
Inverter Mfg/R&D (DOE)	PVManufacturing program has addressed inverter manufacturability & performance. Many supported manufacturers have merged, been acquired or are out of business.	Market did not develop for the module-scale inverters developed. Performance has improved with some designs.	Versatile inverters that are certified and easily connected to the source and the utility.	Custom designs result in performance deficiencies. Performance specs from manufactures are not standardized or regulated.
SBIR – (Industry/DOE)	Optical isolation being developed. Heat pipe cooling being developed.	No optically coupled high power systems are available today. Widely varied emergency power market.	Thermal solutions needed Optical coupling for drives, instruments, etc needed.	Emergency systems must perform as expected. High power systems today are base on scaled lower power hardware.

Table 10.2a.	**“Cost” Related Perspectives from Industry Presentations/Discussions**			
Representation	**Status**	**Market**	**Needs**	**Issues**
Photovoltaics (Industry)	Both utility interactive and stand-alone are available High failure rates still being recorded Some interconnection issues still need resolution	\$0.60 to \$1.00/W depending on power rating	Standard Warranty > 5Yrs Cost < \$0.50/W	Cost is important and needs to come down, but reliability is more important. Cost now 10% - 20% of system
Energy Storage and DER (Industry)-	Mature products are a multi-billion \$ market today Emerging segment is still small but growing Inverter hardware exists	Energy device sales = \$15 B. Inverters must be reasonably priced.	New designs for new applications. Factory systems with combined storage device/inverter packaging. Higher manufacturing volumes needed.	Increasing opportunities for energy management but means \$ for investments Strong demand for improved power quality Can reliability trade off with cost? YES but high reliability is the number one priority. How much reliability is needed?
Electric Vehicle (Industry)	Cost is the overriding figure of merit and is a barrier today. Present costs too high.	RV market does not demand the lowest cost but < \$1/W required. Motive power is just emerging for cars and trucks. Need \$0.06 to \$0.10/W motive power inverters.	Need low cost. (6-10¢/W) Need small size. Needs to be rugged and withstand vibration, shock and extreme temperatures associated with vehicles.	Mass production of motive power still not established.

Table 10.2b.	"Cost" Related Perspectives from DOE Presentations/Discussions			
Representation	**Status**	**Market**	**Needs**	**Issues**
Solar (Photovoltaic) – (DOE)	High Reliability Inverter Development Initiative is focused on reducing costs. Costs have been relatively high in the past due to custom designs. Costs are improving. Future collaboration with other technologies can result in modular inverters and lower costs.	Markets are growing Markets are demanding lower costs.	High quality inverters needed at reasonable costs. Inverters need to undergo HALT tests to assure lower life-cycle costs. UL listing of standard designs will lower costs.	Cost is 10-20% of system but is not #1 priority to bring cost down. Cross-cutting of technologies could lower costs.
Energy Storage and DER (DOE)	About 30% of system cost today New ETO switching devices are being developed. New ETO inverters are being tested in systems	Represents a multi-billion dollar market. Potential for just peak shaving estimated at 460 GW (nearly cost effective for some applications) Hybrid/Village power for 1/3 of the world population	Need both utility-interactive and stand-alone NEED BETTER INVERTERS OR IT WON'T HAPPEN Costs are important but reliability is more important.	Success of energy storage depends on improvements in inverter costs and performance Reliability is a necessity Energy storage won't happen without better inverters.
Transportation (DOE)	Developing improved inverter topologies to use less expensive power semiconductors.	Costs reported as a barrier.	High power density to reduce costs. Need to develop low cost dielectrics for capacitors.	High current densities result in higher costs today/
Inverter Mfg/R&D (DOE	Costs have been reduced through improved manufacturability, fewer components and more integration.	Market not large enough for mass production for PV only. Costs will be very competitive in the future.	Standard modular inverter not commercially available but could reduce costs.	Costs must be reduced.
SBIR – Industry/DOE	Development goals are $150/kVA at 99% efficiency.	Considerable life cycle cost deductions could be possible with heat pipe cooling.	Need optical coupling for drives and sensors to reduce life cycle costs.	Few cost effective topologies available for high power applications.

Table 10.3a.	“Reliability” Related Perspectives from Industry Presentations/Discussions			
Representation	**Status**	**Market**	**Needs**	**Issues**
Photovoltaics (Industry)	Infancy Failure now > 5%	Infancy failures puts a bad light on PV systems	MTBF ~10 Years Life Expectancy ~ 25 Years Low Infancy Failure <<1%	Reliability is the #1 priority today
Energy Storage (Industry)-	Most systems require 1 – 2+ years warranty There is lots of real world data for small systems but larger system need calculations for reliability Current MTBF ranges from 20,000 to 80,000 hours. (2.2 to 8.8 years for continuous operation)	Overall lifetime must be consistent with the application. Reliability is essential.	Higher reliability and methods for predicting needed Enhanced reliable communications needed. Support for emerging technologies needed Higher reliability	How do you measure reliability? Is degradation acceptable? NO for most applications.
Electric Vehicle (Industry)	Reliability needs vary with the applications. Applications vary from motive drives to ancillary power supplies and lighting ballasts.	Market is just emerging for motive drives. (High Reliability is essential) RV and stand-alone market already established.	10-year, 150,000 mile, 5000 operating hour life. Packaging for high reliability needs studies.	New metric for inverters suggested. (10 year, 150,000 mile, 5000 hour) New metrics for all inverters should be examined/

Table 10.3b.	"Reliability" Related Perspectives from DOE Presentations/Discussions			
Representation	**Status**	**Market**	**Needs**	**Issues**
Solar –(Photovoltaic) (DOE)	New emphasis on high inverter and system reliability. Future collaboration can result in synergistic modular designs resulting in higher reliability.	Market beginning to demand high reliability and performance based systems.	Greater than 10-year MTBF by 2004	Cross-cutting of technologies for inverter development would provide some synergism and improved inverter reliability. DOE program needs to pursue the methods for collaborative inverter development.
Energy Storage and DER (DOE)	Inverters are commercially available for most technologies	This is a broad topic with a huge range of needs but reliability is crucial. Most electrical outages are less than 15 seconds but result in huge costs $B. where storage with reliable inverters could avoid many of those costs.	Dispatchable and high reliability inverters could improve the values of unpredictable sources such as PV and wind.	Huge range of inverter needs results in custom designs and lower reliability today.
Transportation (DOE)	Reliability needed with a 15-year lifetime.	Reliability will be essential for the market to develop.	Inverter integration with the motors is required for reliability. 15-year system lifetime needed.	Inverter integration is a barrier today.
Inverter Mfg/R&D (DOE	Reliability has been improved through parts reduction and better manufacturing processes. Fewer errors with automated construction. Soft-switching is being developed to reduce stresses on power semiconductors and improve lifetime.	The market is moving toward grid tied applications. Modularity offers larger market opportunities and flexibility.	Multilevel inverters promise higher reliability through fault tolerance.	Control strategies still need improvements, more integration and standardization.
SBIR – Industry/DOE	Several high reliability packages are being developed ranging from single phase through 5MW. Multilevel inverter being developed. Emergency power must use high reliability inverters	Higher reliability offered with heat pipe cooling.	Optical coupling needed Thermal management needed.	Many of today's high power systems use scaled lower power designs.

10 Breakout Sessions

The breakout sessions were divided into two groups. Group 1 was asked to focus on **"High Reliability Inverter Requirements"** and Group 2 was asked to focus on **"Low Cost Inverter Requirements."** The two groups maintained nearly the same participants for all breakout sessions. The breakout sessions consisted of two point-in-time-related constraints. The first was **"WHAT IS NEEDED?"** and the second was **"WHERE TO GO FROM HERE."** The objective of the "What Is Needed?" session was to brainstorm all relevant topics and issues as a full group. Each of the breakout sessions concluded with a breakout interim report from each group. The "Where to Go From Here?" sessions then used the collection of information compiled in the "What Is Needed?" session to further analyze "Where To Go From Here?" The groups were further divided into teams of 5 sub-categories related to system applications. Those sub-categories were:

i) Residential
ii) Off-grid
iii) Utility
iv) Commercial
v) Village Power

10.1 What Is Needed?

The "What is Needed?" session consisted primarily of a brainstorming session where each participant was asked to list three important issues associated with each of three partitioned subjects and important to a systems-driven approach to inverter development. The three partitions consisted of:

1. Markets and Applications
2. Systems and Subsystems
3. Components and Materials

10.1.1 High Reliability Group "Markets and Applications" Brainstorming Topics

The High Reliability Group was asked to list all issues associated with markets and applications for inverters. The following scoring method was generated. The participants were asked to rate the top three by scoring the highest importance with a (5), second highest with a (3), and next highest with a (1). The scores were collected from each of the subcategories of systems. The scores were then averaged. The High Reliability Group scores were used as the reference; therefore there was no normalization step. Thus the highest possible score for the High Reliability Group scores was (5). The order of the first six topics shown in Table 10.4 is in the order of highest importance to lower importance with the raw score in brackets. The order of the topics below the top six has no significance as to priority or importance but the scores are given.

High Reliability Group's List of Topics Related to Markets and Applications with the Top Six Ranked		
Rank	**Topic**	**Score**
1	Reliable Utility Interface	[2.60]
2	Transparent	[1.60]
3	Smart (Plug-n-play)	[1.20]
4	Life-cycle Cost	[1.20]
5	Source Characteristics (PV, Fuel Cell, etc.)	[1.00]
6	Environment	[0.60]
	Installations (plug-n-play)	[0.60]
	Output Size	[0.20]
	Centralized versus Decentralized	
	Compatible with System-level Protection	

Table 10.4. High Reliability Group Average Ranks of Importance for "Markets and Applications" Topics for Inverters

10.1.2 High Reliability Group "Systems and Subsystems" Brainstorming Topics

The High Reliability Group was next asked to list all issues associated with systems and subsystems for inverters. The list shown in Table 10.5 was generated. The same scoring and averaging was used. The order of the first six topics again is in the order of highest importance to lower importance. The order of the topics below the top six again has no significance as to priority or importance.

High Reliability Group's List of Topics Related to Systems and Subsystems with the Top Six Ranked		
Rank	**Topic**	**Score**
1	Packaging	[3.00]
2	Communications	[1.80]
3	Self-protection	[1.60]
4	Modularity	[1.60]
5	Operational Algorithms	[1.00]
6	Interconnect Commonality	[0.20]
	High Efficiency (thermal)	
	Component Production Availability	
	Local Energy Storage	

Table 10.5. High Reliability Group Average Ranks of Importance for "Systems and Subsystems" Topics for Inverters.

10.1.3 High Reliability Group "Components and Materials" Brainstorming Topics

The High Reliability Group was finally asked to list all issues associated with "Components and Materials" for inverters. The list in Table 10.6 was generated. The same scoring and averaging was used. The order of the first six topics again is in the order of highest importance to lower importance. The order of the topics below the top six again has no significance as to priority or importance.

High Reliability Group's List of Topics Related to Components and Materials with the Top Six Ranked		
Rank	**Topic**	**Score**
1	Passive Components (Inductor, Capacitor etc.)	[3.00]
2	Reliable, Low-cost Switchgear	[2.80]
3	Testing and Quality Control (QC)	[1.60]
4	Advanced Control Algorithms	[1.20]
5	Advanced Packaging	[0.20]
6	Compatibility with Automated (Advanced) Assembly	[0.20]
	General Non-hazardous Materials	
	Power Devices	
	Advanced Installation Technologies	
	Multi-source Components	
	Installation	

Table 10.6. High Reliability Group Average Ranks of Importance for "Components and Materials" Topics for Inverters

10.1.4 Low Cost Group "Markets and Applications" Brainstorming Topics

The Low Cost Group was also asked to list all issues associated with markets and applications for inverters. The following list was generated. The participants were asked to rate the top three by scoring the highest importance with a (3), second highest with a (2), and next highest with a (1). The scores were reported and collected from each of the subcategories of systems with no distinction as to which subcategory contributed to the total score. The scores were then averaged and normalized. The High Reliability Group scores were used as the reference, therefore there was a normalization step consisting of changing all the (3) scores to (5) and all the (2) scores to (3). Thus the highest possible score for the Low Cost Group scores was then also (5). The order of the first six topics shown in Table 10.7 is in the order of highest importance to lower importance with the raw score in brackets. The order of the topics below the top six has no significance especially where no score is reported, as to priority or importance but some scores are given.

Low Cost Group's List of Topics Related to Markets and Applications with the Top Six Ranked		
Rank	Topic	Score
1	Plug-n-power (in residential buildings)	[3.09]
2	Commercial (as in schools, super markets)	[2.27]
3	New Construction	[1.82]
4	Utility-scale (behind the fence (all RE))	[1.55]
5	Emergency Services	[0.27]
6	Military/mobile	[0.09]
	Village Power	
	Commercial (high-rise buildings)	
	Demand Support and Storage	
	National Parks	
	Telecommunication	
	What Will the Distribution Systems be in 2025? Will There be a Distribution System by 2025?	
	Industrial facility (active power compensation)	
	Micro Applications (like mini-refrigerators)	
	Agricultural	
	Standard Applications	
	Changing the National Electrical Code to Make the System Cheaper	
	Indoor vs. Outdoor	

Table 10.7. Low Cost Group Average Ranks of Importance for "Markets and Applications" Topics for Inverters.

10.1.5 <u>Low Cost Group "Systems and Subsystems" Brainstorming Topics</u>

The Low Cost Group was also asked to list all issues associated with systems and subsystems for inverters. The list shown in Table 10.8 was generated. The same scoring, averaging and normalizing was used for the Markets and Applications for the low cost group was used. The order of the first six topics again is in the order of highest importance to lower importance. The order of the topics below the top six again has no significance as to priority or importance.

Low Cost Group's List of Topics Related to Systems and Subsystems with the Top Six Ranked		
Rank	**Topic**	**Score**
1	High Reliability	[4.64]
2	Low Cost (lifetime)	[1.55]
3	Low Maintenance	[1.00]
4	Standardized Performance Reporting (standards)	[0.73]
5	Standard Human Interface	[0.55]
6	Standard Communications	[0.46]
	Low Noise (all acoustic RF)	
	Built with Common Components	
	Heat Dispersion and Control (thermal management)	
	Self Calibrating (atomic clock)	
	Serviceability	
	Move Anti-islanding Control out of the Inverter to the Grid	
	Intentional Islanding (micro-grids)	
	Interoperability	
	Dispatch and Storage	
	Ownership	
	AC versus DC (over 50 years)	

Table 10.8. Low Cost Group Average Ranks of Importance for "Systems and Subsystems" Topics for Inverters.

10.1.6 Low Cost Group "Components and Materials" Brainstorming Topics

The High Reliability Group was next asked to list all issues associated with "Components and Materials" for inverters. The list in Table 10.9 was generated. The same scoring and averaging was used. The order of the first six topics again is in the order of highest importance to lower importance. The order of the topics below the top six again has no significance as to priority or importance.

Low Cost Group’s List of Topics Related to Components and Materials with the Top Six Ranked		
Rank	**Topic**	**Score**
1	Low-frequency Energy Storage (capacitors)	[3.29]
2	Thermal Management	[1.57]
3	Physical Packaging/Protection	[1.14]
4	Control Algorithms	[0.71]
5	Magnetics (low- & high-frequency)	[0.57]
6	Semiconductors	[0.57]
	Human Interface	[0.43]
	Reliable (low-cost) Switchgear	[0.14]
	High-frequency Energy Storage (dealing with switching)	[0.14]
	Codes Compliance	[0.14]
	Models	
	Sensors (utility-grade power measurement)	
	Environmental Issues (toxic, disposable)	
	Security	
	Communication Interface (human)	
	Self Diagnostics	
	Safety issues	
	Circuit Boards/Bus work/Interconnections	
	Shipping Weight and Form Factor	
	Conductors	
	Distribution	
	Manufacturing/Labor	
	Input and Output?	
	Indoor vs. Outdoor	
	Upload Ability	

Table 10.9. Low Cost Group Average Ranks of Importance for “Components and Materials” Topics for Inverters.

10.1.7 Graphic Representations of the Priority Topics

The figures in 10.1.7 show the graphic representations of the top six topics for each group in each market category. The graphs of both groups (high reliability and low cost) for each market category are placed on the same page to give the reader easy comparisons to the relative magnitudes of importance as well as finding topic similarities.

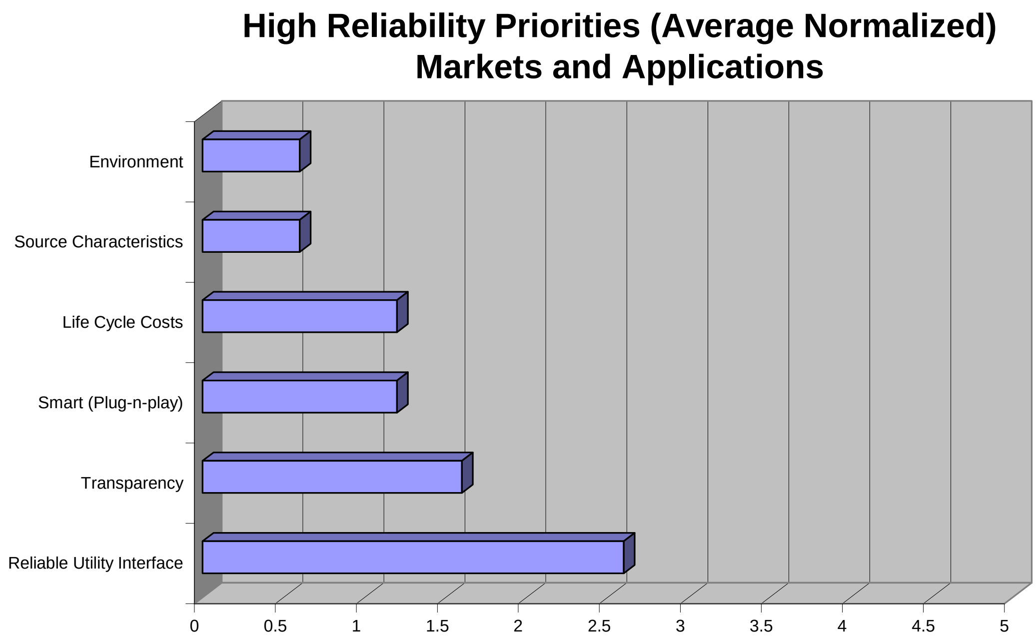


Figure 10.1a. Graph Showing Relative Importance of High Reliability Inverter R&D Needs When Viewed from the Markets and Applications Perspective

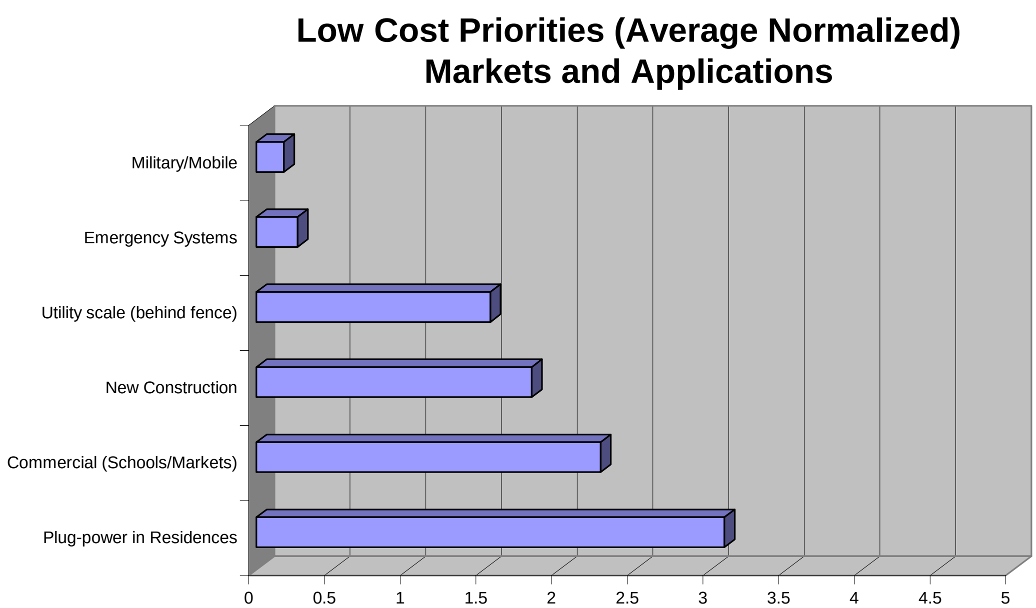


Figure 10.1b. Graph Showing Relative Importance of Low Cost Inverter R&D Needs When Viewed from the Markets and Applications Perspective

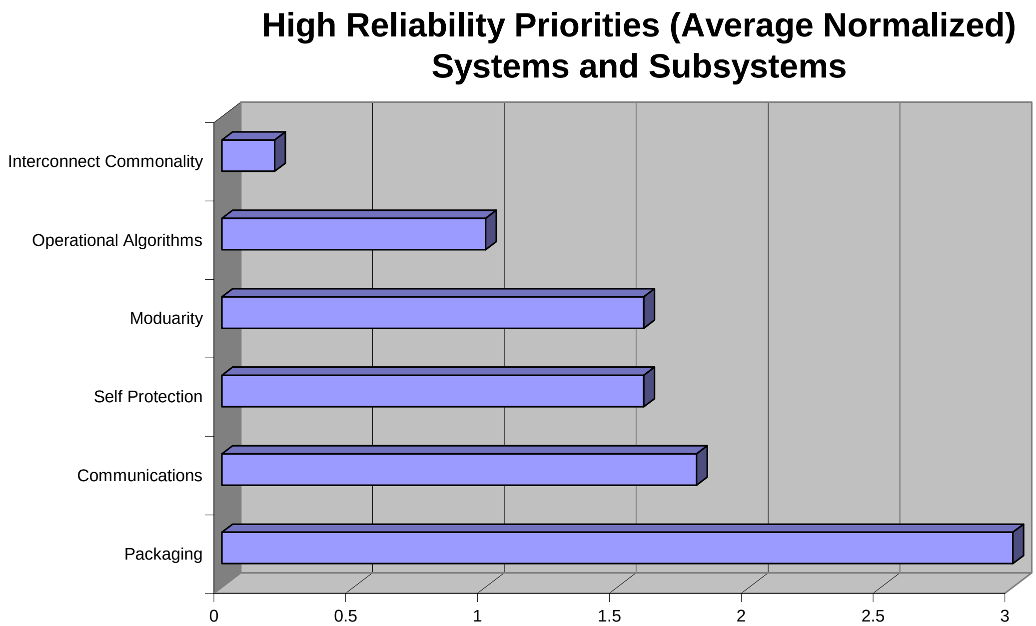


Figure 10.2a. Graph Showing Relative Importance of High Reliability Inverter R&D Needs When Viewed from the Systems & Subsystems Perspective

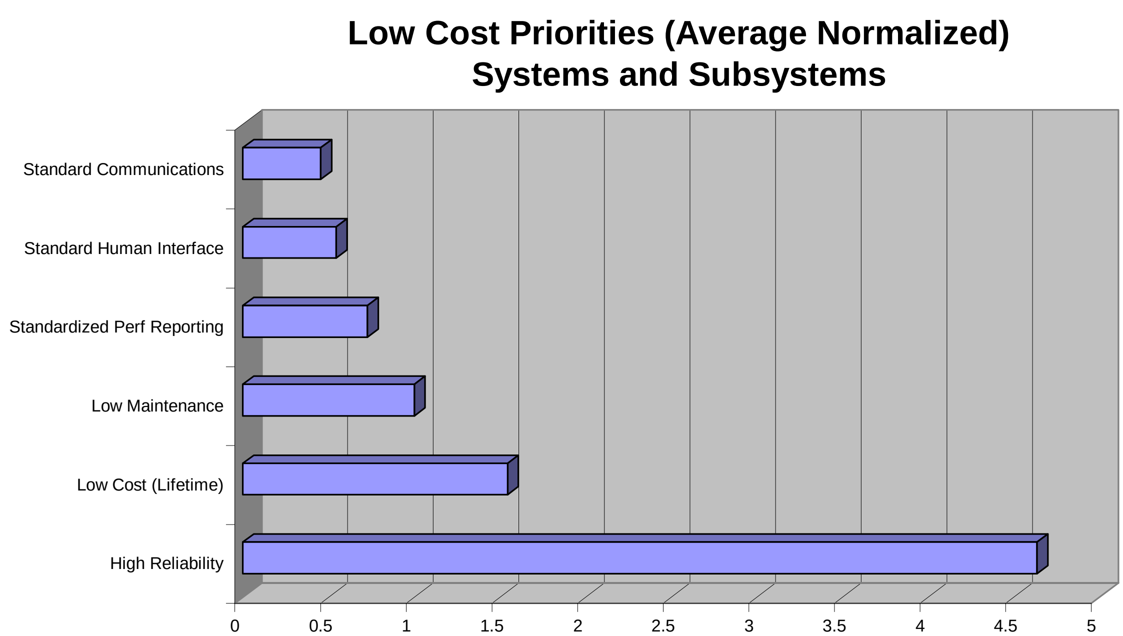


Figure 10.2b. Graph Showing Relative Importance of Low Cost Inverter R&D Needs When Viewed from the Systems & Subsystems Perspective

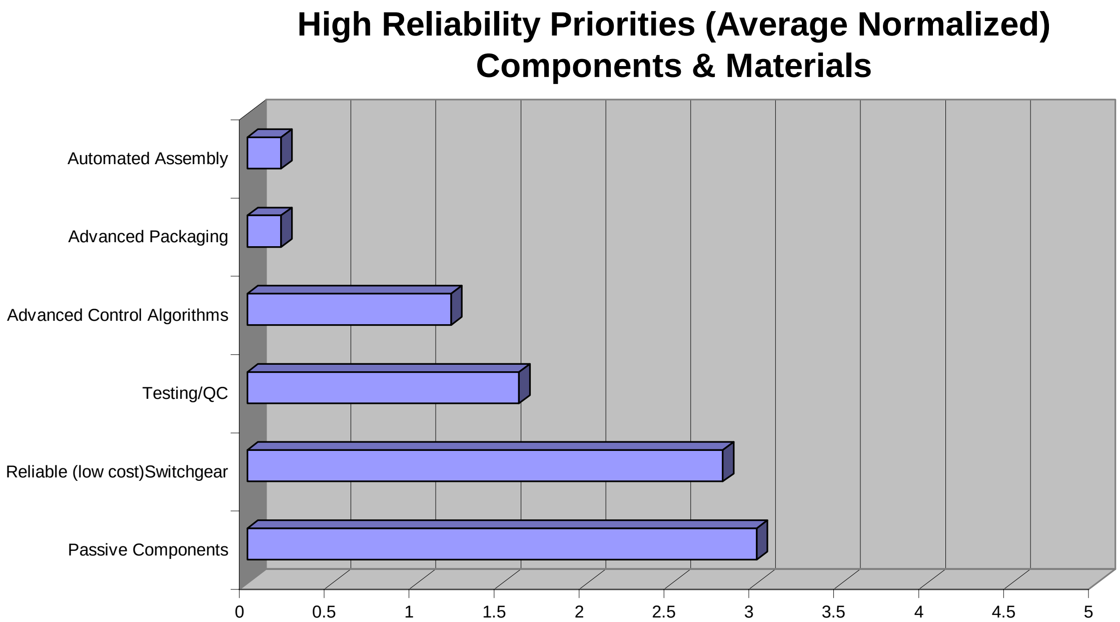


Figure 10.3a. Graph Showing Relative Importance of High Reliability Inverter R&D Needs When Viewed from the Components and Materials Perspective

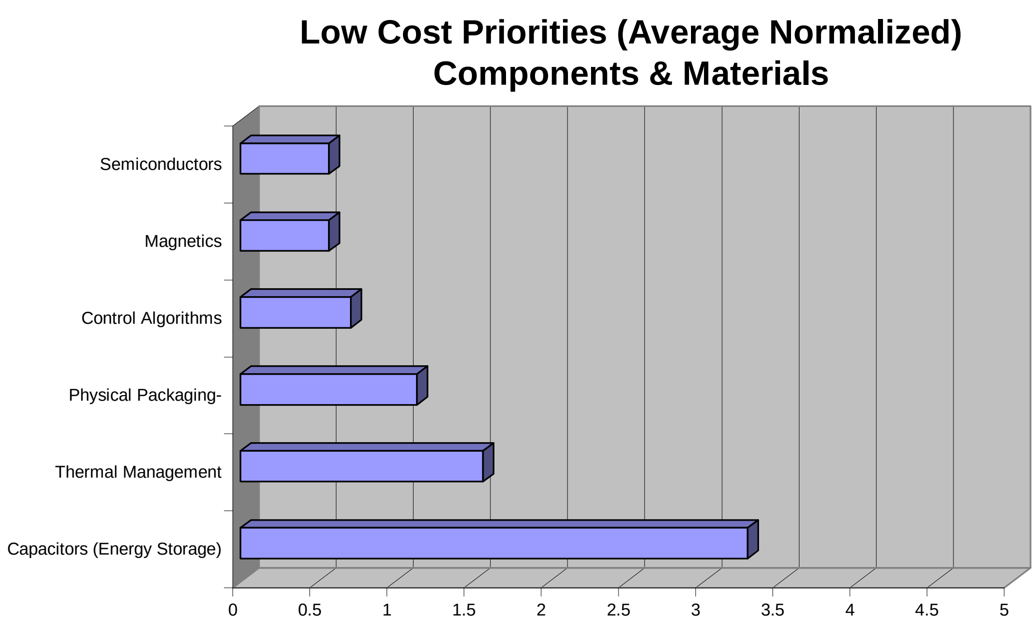


Figure 10.3b. Graph Showing Relative Importance of Low Cost Inverter R&D Needs When Viewed from the Components and Materials Perspective

11 Summary of Findings

This section summarizes the needs, goals and findings of the breakout sessions relative to the type of inverter application. Section 10 of this report provided a set of priorities with respect to the markets and applications, systems and subsystems, and materials and components. This section will further explore the data to provide a summary of the information collected with respect to inverter research and development needs and goals for residential, commercial, utility, off-grid, and village power applications. The residential, commercial and utility inverter needs and goals explored in this section are for utility-interactive applications. Stand-alone applications are explored as part of the off-grid and village power needs and goals.

11.1 Inverter Research and Development Needs

11.1.1 <u>Needs and Goals for Residential Inverters</u>

The residential inverter R&D needs analyzed here are for grid-tied applications and may be building integrated or retrofit applications. The residential inverter is typically rated at 1 – 10 kW and operates into a single-phase utility service in the United States, Canada and Mexico. The output voltage may be 120V or 240 V at 60 Hz in these countries, but is different voltages and frequencies in most other countries. The input voltages for residential inverters appear to fall into two categories. The low voltage inverters typically operate at 24 or 48 Vdc. The high voltage inverters operate between 300 and 600 Vdc. Many of the inverters using higher dc voltage are referred to as string inverters for photovoltaic applications. Residential size inverters for fuel cells, micro turbines and load leveling are just emerging into the commercial markets.

Higher reliability and lower cost were key needs and were discussed in detail. Reliability was the major concern, but the cost of reliability often tempered the discussions. One consensus was the increased cost for improved reliability must be affordable for the original owner. A 10-year MTFF emerged as a short-term goal with further improvement expected with volume production, standard designs and more integration. The question of serviceability was discussed and the breakout groups concluded that a “dime-a-watt” residential inverter couldn’t be manufactured for servicing or for 30-year lifetimes.

The issue of infant mortality was discussed separately from reliability. One estimate of infant mortality today for residential inverters placed a 5% early failure rate. It was concluded an infant mortality rate of 1% would be acceptable in the near term but further improvements were needed in the long term. This rate included the dead-on-arrival inverters in today installations.

A cost goal of $0.20/W with a 5-year warranty for individual purchases emerged. The cost goal for quantity purchases was $0.10/W for a 3- 5-kW inverter, but this inverter would most likely be a throwaway and not serviceable. The concept of throwaway inverters requires quick and easy interconnect designs on both the dc and ac side. The concept of an AC PV Building Block was discussed briefly and the concept was endorsed if the costs were low enough to be competitive with conventional systems once ease of installation was factored in.

Other key characteristics were discussed and are listed here, but no firm consensus was drawn. Plug-and-play installations were discussed extensively and the idea was firmly endorsed, but it is most likely a mid- or long-term advancement. In the interim, listed integrated systems will serve as easier and standard installations. Smart self-diagnostics were listed as very desirable but the costs and possible decrease in reliability due to false indications must be considered. Transparency of the system is very important and the inverter and system needs to be designed to be unobtrusive and environmentally friendly (low or no noise). Thermal management was mentioned as a short term need for inverters. Inverters that turn off or cut back power throughput with elevated temperatures are commonplace today but thermal management must be improved. Fans are undesirable in residential inverters. When used, they should only run when needed and should be quiet and easily exchanged.

Inverters with more flexible inputs could be used for synergistic applications such as PV and fuel cells. Inverters that have separate inputs with individual maximum power point trackers were listed as needed in the near term. This would allow a single inverter with multiple inputs to be used in systems where individual energy sources vary slightly. It would also improve the energy utilization factor. Inverters with flat efficiency characteristics of 95% are desirable.

11.1.2 Needs and Goals for Commercial Inverters

Commercial inverters are typically three-phase output with a narrowed range of dc voltage operating characteristics. Higher voltage dc is typical because of the magnitude of current required for lower voltages. The commercial inverters were defined with power ratings between 10kW and 100kW.

Today's reliability of the commercial inverters was considered acceptable by some of the group participants. Lifetime and lifecycle costs were considered more important for commercial inverters, but a 30-year life was deemed unnecessary.

Costs today were reported at approximately $0.60/W today, but a goal of $0.225/W was called for by 2020 in order to generate power at 6 cents/kWh. A $0.10/W inverter was considered disposable for the commercial inverters.

The efficiency of commercial inverters is in the 92-95% range and could be improved. A 98% goal was considered achievable by the year 2020. Efficiency is important because it drives installation and operation costs.

11.1.3 Needs and Goals for Utility Inverters

The utility inverters are often similar to the commercial inverters with the same ranges of input and output voltages. Utility inverters were considered to be reliable enough today with 99.5% availability reported by one utility with the caveat that a better statistical database is needed. The performance of the inverter appeared to be more important with a need to reduce nuisance trips to less than 1 per 10MW per year.

Inverters for utility application were reported as costing as low as $0.30/W today because of quantity purchases. Inverter manufacturers reported that for every 1% increase in production volume there is a ½% decrease in price. The floor on that trend was set at $0.20/W.

Other pertinent goals and needs for the utility inverter included a call for collecting reliability and efficiency data for benchmarking. Collaborative efforts were begun with Sandia National Laboratories as a result of these workshop discussions.

11.1.4 Needs and Goals for Off-grid Inverters

The needs and goals for inverters for off-grid applications were very similar to those of village power and are included in the village power section below.

11.1.5 Needs and Goals for Village Power Inverters

Cost is the main driver for the installation of village power systems, but reliability is ultimately the sustainability driver. The village power inverter must be capable of regulating the line voltage and frequency and often contains components and circuits to regulate the charge or charging methodology of a battery. These inverters must also provide for surge currents to start motors or to handle short-term surges. The general comments regarding the cost of these inverters was "the life cycle system cost must be less than a diesel generator alternative except where the diesel is an unacceptable source because of noise or pollution concerns." General goals for cost of village power should be converted to $/kWh rather than $/W installed as is often used today. A long-term value goal in terms of energy for a residential stand-alone system (with inverter) should be $0.10/kWh. The inverter lifetime should be quoted in terms of years and kWh. One suggestion for a goal for lifetime would be 10 years or 20,000 kWh. Inverter efficiency numbers should account for maximum power point tracking or source utilization factors. The tare loss of an inverter affects the utilization factors especially when tare loss when the source is not producing power is significant. Another way to express efficiency would be in terms of a weighted energy throughput where the inverter efficiency value is integrated over the time for a typical day or year of operation.

Other factors that need consideration for village power inverters include the ease to transport, modularity and redundancy, lower voltage for safety, and ease of maintenance and operation. The efficiency of the village power was generally judged less important than for other applications but the $/kWh was important.

11.2 Needs for Leapfrog Technology Advances

Inverters are expected to follow an evolutionary path for advances in the near term. Leapfrog advances can come from designs and applications for mass production or from the component side when new devices such as long life capacitors, highly integrated controls, or fully packaged bridge assemblies appear. Leapfrog advances will be needed to implement fully "plug and play" systems. Some leapfrog advances in magnetic components or fully integrated control strategies would provide incremental jumps in inverter performance and probably reliability.

11.3 Needs for Modeling

The needs for modeling were discussed in several sessions. There was a consensus that modeling is needed both in the short term and for the long term. It is not too late to incorporate modeling into inverter R&D and in fact some modeling is emerging. Further, modeling must be an essential part of a "DOE 5-year Plan for Inverter Research and Development."

An short list of available models was collected during the workshop. Some of the key models that could be incorporated into an ADVISOR like inverter R&D model included:

- SPICE/SABRE
- D-SPACE
- Clean-power estimator

11.4 Parking Lot Issues

Many topics and issues emerged during the course of the workshop that were judged too require too much time, needed further input, or needed extended discussions. These issues were listed in a "parking lot" for reference and for future workshop topics. The parking lot issues included:

1. The interface of solar systems: installation AND service.
2. AC PV modules – where do they fit?
3. Is it useful to shoot for high-reliability inverters in 3 years?
4. Need to define reliability, efficiency, and cost (include core and installed $/kW) still exist
5. How do we measure MTBF or MTFF?
6. Need life-cycle cost models for inverters and systems
7. How many inverter ranges need to be modeled? 3?
8. Modeling of high frequency switchgear is needed
9. Documentation of installation procedures is needed
10. Codes and standards (DOE should remain proactive)
11. Increase Sandia resources.

12 Bibliography

[1] Lee, F.C., Van Wyk, J.D., Boroyevich, D., Jahns, T., Chow, T.P., Barbosa, P., *Modularization and Integration as a Future Approach to Power Electronics Systems*, Report for the National Science Foundation, 2002.

[2] Lee, F.C., Van Wyk, J.D., Boroyevich, D., Jahns, T., Lorenz, R.D., Chow, T.P., Gutmann, R.J., Barbosa, P., *An Integrated Approach to Power Electronics Systems*, Report for National Science Foundation, 2002.

[3] Van Wyk, J.D., Lee, F.C., *Power Electronics Technology at the Dawn of the New Millennium-Status and Future*, Proceeding of the IEEE 1999.

[4] Kerkman, R.J., Skibinski, G.L., Schlegel, D.W., "AC Drives: Year 2000 (Y2K) and Beyond," *IEEE-APEC*, Mar 1999.

[5] Motto, K., Yuxin, L., Huang, A., *Comparison of the State-of-the-art High Power IGBTs, GCTs, and ETOs*, Virginia Power Electronics Center.

[6] Carroll, E., Galster, N., *IGBT or IGCT: Consideration for Very High Power Applications*, ABB Semiconductors AG, Oct 22, 1997.

[7] Bernet, S., Teichmann, R., Zuckerberger, A., Steimber, P., *Comparison of High Power IGBTs, GCTs, and ETOs*, Virginia Power Electronics Center.

[8] Carroll, E., Galster, N., *IGBT or IGCT: Considerations for Very High Power Applications,* ABB Semiconductors AG, Oct 22, 1997.

[9] Atcitty, S., Ranade, S., Grey-Fenner, A., *Summary of the State-of-the-art Power Conversion Systems for Energy Storage Applications*, SAND98-2019, Sep 1998.

[10] Atcitty, S., Zhang, L., Shen, C., Crow, M., Yang, Z., "Integration of a StatCom and Battery Energy Storage", *IEEE Transaction on Power Systems*, May 2001. Akhil, A., Swaminathan, S., Sen, R., *Cost Analysis of Energy Storage Systems for Electric Utility Applications,* SAND97-0443, Feb 1997.

[12] Mohan, N., Undeland, T.M., Robbins, W.P., *Power Electronics: Converters, Applications, and Design*, 3rd Edition, John Wiley and Sons (2002) ISBN: 0-471-22693-9.

[13] Taylor, P., Johnson, L., *A Summary of the State of the Art of Superconducting Magnetic Energy Storage Systems, Flywheel Energy Storage Systems, and Compressed Air Energy Storage Systems*, SAND99-1854, Jul 1999.

[14] Tarter, R., *Solid-state Power Conversion Handbook, John Wiley and Sons*, 1993.

[15] Ericksen, Hamilton, Campisi, Whitcomb, Borraccne, Jacobson, *Standardized Power Switch System Modules*, PCIM Power Electronics Institute, Power Semiconductor Specialist Course Notes, Power System World, 1997.

[16] Bower, W., *Inverters-Critical Photovoltaic Balance-of-system Components: Status, Issues, and New-millennium Opportunities*, Progress in Photovoltaics Applications 8, 2000.

[17] Inverter Price Environment, www.solarbuzz.com/inverterprices.htm, Mar 27, 2003.

[18] Kaporch, T., *Electronic Motor Drive Market To Top &19 Billion in 2005*, www.quicksitebuilder.cnet.com/tkaporch/drivesresearch/id8.html. Mar 27, 2003.
[19] *AC/DC Power Supplies: Worldwide Market Forecasts, Competitive Environment and Industry Trends*, www.darnell.com/services/01-acmkt.stm, Mar 27, 2003.
[20] Goodwin, M., Andrews, N., *An Executive White Paper On: Battery Powered Uninterruptible Power Supplies North America, Europe, Asia-Pacific, Latin America*, www.vdc-corp.com, Mar 27, 2003.
[21] Gaboriault, M., Plante, Andrews, J., N., *An Executive White Paper On: The North American Market For Grid Power Solutions: Distributed Generation & Ride-Through Technologies*, www.vdc-corp.com, Mar 27, 2003.
[22] Celanovic, I., Celanovic, N., Milosavljevic, I., Boroyevich, D., Cooley, R., *A New Control Architecture for Future Distributed Power Electronics Systems*, Virginia Polytechnic Institute and State University, 2000.
[23] Chow, T.P., *High-Voltage SiC and GaN Devices for Power Electronics Applications*, Presentation by Dr. Chow, Rensselaer Polytechnic Institute, Sep 11, 2002.
[24] *Trends in Photovoltaic Applications in Selected IEA Countries between 1992 and 2001*, International Energy Agency Photovoltaic Power Systems, Report IEA-PVPS T1-11: 2002.
[25] Stevens, J., Bonn, R., Ginn, J., Gonzalez, S., Kern, G., *Development and Testing of an Approach to Anti-islanding in Utility-Interconnected Photovoltaic Systems,* SAND2000-1939, Published by Sandia National Laboratories, Albuquerque, NM, Aug 2000.
[26] Bower, W., Thomas, H., Kroposki, B., Witt, E., Bonn, R., Ginn, J., Gonzales, S., "Testing To Improve PV Components and Systems," Proceedings of the 16th European PV Solar Energy Conference and Exibition, Glasgow, UK, May 1-5, 2000.
[27] Bower, W., Thomas, H., Kroposki, B., Witt, E., "Progress in Photovoltaic Components and Systems," Proceedings of the 16th European PV Solar Energy Conference and Exibition, Glasgow, UK, May 1-5, 2000.
[28] *IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems*, Sponsored by IEEE Standards Coordinating Committee 21 on Photovoltaics, IEEE Std/. 929-2000. Published by the IEEE, New York, NY, April 2000.
[29] *UL Standard for Safety for Static Converters and Charge Controllers for Use in Photovoltaic Power Systems, UL1741,* Underwriters Laboratories, Second Edition, Jan 2001.
[30] Stefanac, D., "Process Quality in Manufacturing PV Power Conversion Products," Progress in Photovoltaics Research and Applications, published by John Wiley & Sons, Volume 7, Number 3, May-Jun 1999.
[31] Thomas, M., Post, H., DeBlasio, R., "Photovoltaic Systems: An End-of-Millennium Review," Progress in Photovoltaics Research and Applications, published by John Wiley & Sons, Volume 7, Number 1, pp 1-19, Jan-Feb 1999.

[32] Ropp, M., Begovic, M., Rohatgi, A., "Prevention of Islanding in Grid-connected Photovoltaic Systems," Progress in Photovoltaics Research and Applications, published by John Wiley & Sons, Volume 7, Number 1, Jan-Feb 1999.
[33] Utility Aspects of Grid Interconnected PV Systems, IEA-PVPS Report, IEA-PVPS T5-01: 1998, Dec 1998.
[34] Kern, G., SunSine™300: Manufacture of an AC Photovoltaic Module, A PVMaT contractors Final Report by Ascension Technology, Phases I & II, NREL/SR-520-26085, Golden, CO, Mar 1999.
[35] Bonn, R., Ginn, J., Hund, T., Gonzalez, S., Ralph, M., Strommen, R., "Sandia National Laboratories Photovoltaic Balance of Systems Program," Proceedings of the 15th Conference, NCPV Program Review, Denver, CO, Sep 1998.
[36] IEEE Guide for Terrestrial Photovoltaic Power System Safety, Sponsored by IEEE Standards Coordinating Committee 21 on Photovoltaics, IEEE Std 1374-1998, Published by the IEEE, New York, NY, Sep 30, 1998.
[37] Begovic, M., Ropp, M. Rohatgi, A., Pregelj, A., "Determining the Sufficiency of Standard Protective Relaying for Islanding Prevention in Grid-Connected PV Systems," Proceedings of the 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Hofburg Congress Center, Vienna, Austria, Jul 6-10, 1998.
[38] Thomas, H., Kroposki, B., McNutt, P., Witt, C., Bower, W., Bonn, R., Hund, T., "Progress in Photovoltaic System and Component Improvements," Proceedings of the 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Hofburg Congress Center, Vienna, Austria, Jul 6-10, 1998.
[39] Kern, G., Bonn, R., Ginn, J., Gonzalez, S., "Results of Sandia National Laboratories Grid-Tied Inverter Testing," Proceedings of the 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Hofburg Congress Center, Vienna, Austria, Jul 6-10, 1998.
[40] Kobayashi, H., Takigawa, K., "Islanding Prevention Method for Grid-interconnection of Multiple PV Systems," Proceedings of the 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Hofburg Congress Center, Vienna, Austria, Jul 6-10, 1998.
[41] Kleinkauf, W., Bishop, J., Haas, O., Raptis, F., Sachau, J., Zacharias, P., "Standardization of Systems Technology for PV Power Supply - Modular Structures With Series Produced Components," Proceedings of the 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Hofburg Congress Center, Vienna, Austria, Jul 6-10, 1998.
[42] Stern, M., Duran, G., Fourer, G., Whalen, W., Loo, M., West, R., Development of a Low-cost, Integrated 20-kW AC Solar Tracking Sub-Array for Grid-connected PV Power System Applications, A PVMaT Final Technical Report by Utility Power Group, NREL/SR-520-24759, Jun 1998.
[43] Grid-Connected Photovoltaic Power Systems: Status Of Existing Guidelines And Regulations In Selected IEA Member Countries (Revised Version), Task V Internal Report, IEA-PVPS V-1-03, March 1998.

[44] Porter, D., Meyer, H., Leang, W., Three-Phase Power Conversion System for Utility-Interconnected PV Applications, A PVMaT Phase I Technical Progress Report by Omnion Power Engineering, NREL/SR-520-24095, Golden, CO, Feb 1998.
[45] Bower, W., Thomas, H., Kroposki, B., Bonn, R., Hund, T., "Balance-Of-System Improvements For Photovoltaic Applications Resulting From The PVMaT Phase 4A1 Program," Proceedings of the 26th IEEE PV Specialists Conference, Anaheim, CA, Oct 1997.
[46] Kern, G.A., "Interconnect Guidelines and Status of AC PV Modules in the United States," Proceedings of the IEA PVPS Task V Workshop on Utility Interconnection of PV Systems, Zurich, Switzerland, Sep 15-16, 1997.
[47] Bower, W.I., Whitaker, C., "Overview of PV Balance-of-systems Technology Experience and Guidelines for Utility Ties in the United States of America," Proceedings of the IEA PVPS Task V Workshop on Utility Interconnection of PV Systems, Zurich, Switzerland, Sep 1997.
[48] Freitas, C., Development of a Modular Bi-Directional Power Inverter for Photovoltaic Applications, A PVMaT Annual Technical Report by Trace Engineering, NREL/SR520-23401, Golden, CO, Aug 1997.
[49] Welsley, A., Wills, R., Next Generation Three-Phase Inverters, Phase I report by Advanced Energy Systems, a PVMaT report, NREL/SR-520-23330, Golden, CO, Jul 1997.
[50] Stern, M., West, R., Fourer, G., Loo, M., Duran, G., Development of a Low-cost Integrated 20-kW AC Solar Tracking Sub-Array for Grid-connected PV Power System Applications, A PVMaT Annual Technical Report by Utility Power Group, NREL/SR-520-23118, Jun 1997.
[51] Odenkamp, H., deJong I., Baltus, C., Verhoeven, S., Elstgeest, S., "Reliability and Accelerated Life Tests of the AC Module-mounted OKE4 Inverter," Proceedings of the 25th IEEE Photovoltaic Specialists Conference, Washington, DC, May 13-17, 1996.
[52] Wills, R., Hall, E., Strong, S., Wohlgemuth, J., "The AC Photovoltaic Module," Proceedings of the 25th IEEE Photovoltaic Specialists Conference, Washington, DC, May 13-17, 1996.
[53] Bower, W., "Sandia's PV Program Perspectives on "Smart Power" and Power Integrated Circuit Devices for Photovoltaic Applications," Proceedings of 2nd Workshop on Smart Power/Power Integrated Circuit Technology and Applications, Pasadena, CA, Dec. 8-9, 1994.
[54] Bulawka, A., Krauthamer, S., Das, R., Bower, W., "Photovoltaic Power Conditioners: Development, Evolution, and the Next Generation," Proceedings of the 25th Intersociety Energy Conversion Engineering Conference, Monterey, CA, Aug 8-12, 1994.
[55] O'Sullivan, G., "Trimode Power Converter Optimizes PV, Diesel and Battery Energy Sources," Proceedings of the 1st World Conference on Photovoltaic Energy Conversion, Waikoloa, HI, Dec 5-9, 1994.
[56] Ball, G., Shugar, D., Bower, W., Porter, D., "A Standardized Utility Inverter Test Protocol and Performance Evaluation of an Omnion 3200 Prototype,"

Proceedings of the American Solar Energy Society Annual Conference, Washington, DC, Apr 1993.

[57] Bower, W., Ropp, M., "Evaluation of Islanding Detection Methods for Photovoltaic Utility-interactive Power Systems", SAND2002-3591, Sandia National Laboratories, Albuquerque, NM, Nov 2002.

[58] Bower, W., Whitaker, C., "Certification Of Photovoltaic Inverters: The Initial Step Toward PV System Certification," Proceedings of the IEEE 29th PV Specialist Conference, New Orleans, LA, May 21-24, 2002.

[59] Bower, W., "International Guideline for The Certification Of Photovoltaic System Components and Grid-Connected Systems", International Energy Agency Photovoltaic Power Systems Implementing Agreement, Task V; Grid Interconnection of Building-Integrated and Other Dispersed Photovoltaic Power Systems, Report IEA PVPS T5-06: 2002, Feb. 2002.

[60] Bower, W., Ropp, M., "Evaluation of Islanding Detection Methods for Photovoltaic Utility-interactive Power Systems", International Energy Agency Photovoltaic Power Systems Implementing Agreement, Task V; Grid Interconnection of Building-integrated and Other Dispersed Photovoltaic Power Systems, IEA PVPS T5-09: 2002, March 2002.

[61] Bower, W., Ropp, M., "Evaluation of Islanding Detection Methods for Photovoltaic Utility-interactive Power Systems", International Energy Agency Photovoltaic Power Systems Implementing Agreement, Task V; Grid Interconnection of Building-integrated and Other Dispersed Photovoltaic Power Systems, Report IEA PVPS T5-09: 2002, Feb. 2002.

[62] Bower, W., "Certification of Hardware for Photovoltaic Applications," Proceedings of the NCPV Program Review Meeting 2001, Lakewood, CO, Oct 2001.

[63] Bonn, R., Bower, W., King, D., Moore, "Photovoltaic Systems Reliability Improvement Program," Proceedings of the NCPV Program Review Meeting 2001, Lakewood, CO, Oct 2001.

[64] Bower, W., Whitaker, C., "Certification of Photovoltaic Inverters," Proceedings of the Photovoltaic Systems Symposium, Albuquerque, NM, Jul 18-20, 2001.

Appendix A -
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Appendix B -
List of Questions Asked of Workshop Participants With a Summary of Answers Provided by the Participants

1. Why a 5-year plan for inverter development?

    a. Can a coordinated effort by the cross technologies (DOE Solar, DER, Storage, Transportation, and Others) create an R&D environment that can help to improve the performance, costs and reliability of inverters for all applications?

Answers:
Definitely. The subsidies and incentives in Germany that led to the SMA inverters were very effective. Combining resources among DOE programs could yield tremendous improvements for all.

    b. Can a set of generic inverter cores be used to handle all of the technologies?

Answers:
Yes, but the optimal topology may change as devices improve. The tradeoffs should be continuously re-examined and documented.

Goal is hard to meet. Requirements are too different. e.g. Optimum voltage levels of Batteries, Fuel cells, small wind-turbines, and PV (String-technologies) vary.

Common approach seems possible in the field of grid-tied applications concerning the AC-side control algorithms and technologies of coupling inverters to the mains (e.g. ENS, Anti-Islanding, Dispatchability, Power Quality, etc.).

    c. Can a concerted development plan result in economical inverter MTFF rates of 15 years or more for all applications?

Answers:
Yes, but the failure-rate definitions must be clearly understood. System failures due to misapplication should not count as inverter failures. Failure categories at the component and system level are needed to have meaningful metrics.

    d. Phantom Topic #1: Can this concerted effort result in inverter lifetimes of 30 years?

Answers:
Yes. Despite its crosscutting importance, an effort in this area has never been supported by any DOE program in any consistent manner.

2. What is the state of inverter technologies today and how is it expected to change in the next 5 years?

    a. What is the status of power electronics for all inverter ratings today?

Answer: Mature switching devices exist and are continuously improving.

    b. Where is expected to go?

Answers:
Driven by the large market for motor drives, including automotive, devices will become capable of handling greater power levels and will incorporate protection and controls in the devices themselves.

Transformerless inverters are expected.

    c. Is power electronics the cost drivers in inverter manufacturing? Are inverters the cost drivers in power electronics? What are the cost drivers and tradeoffs?

Answers:
I assume this question refers to switching devices such as IGBT's, FET's, etc. They represent only one cost element. Switching devices are developed in response to motor drive markets, not inverters. Other inverter cost drivers include magnetic components, subsystem assembly, and thermal management. The primary cost driver has been one-of-a-kind control design requirements, which lead to high engineering costs.

PV-area: PE driving PV developments:
Example: Specific Integrated Semiconductor modules for PV-Inverters are not available.
Large Wind is driving PE

Other Cost drivers: Magnetic components, safety issues (e.g. redundant anti-islanding)

Trade-offs: High efficiency - Low EMI, High efficiency – Low cost?

    d. Is power electronics the reliability driver in inverter performance? What are the reliability drivers?

Answers:
No. The lack of standard requirements for system controls and inconsistent installation quality are the drivers.

No: Power electronics components not drivers, but packaging / system integration is driver.

No: Power Electronics packaging is the driver: e.g. Design for thermal cycling.

    e. At what point is a disposable inverter a consideration where cost/reliability tradeoffs make disposable inverters economical?

Answers:
Inverters are disposable today in the same way as computers, stereos, and other appliances.

Repairs of inverters smaller than 5 kW are not and may never be economical.

Never! Costs are too high!

f. Phantom Topic #2: What changes in power electronics technology would significantly improve inverter performance and reliability?

Answers:
Lower-loss switches would reduce heat-rejection requirements, but switches are is not the primary reliability drivers.

Power Electronics packaging!

3. What are the major markets for inverters today?

    a. Can several standard inverter designs serve a majority of the markets?

Answers:
Yes. This is a major goal a high-reliability inverter initiative currently under way. Core inverter can be married with different dc-to-dc converters. Energy storage sets voltage requirements.

    b. What markets are synergistic enough to use common inverter technologies?

Answers:
It includes most distributed generation including PV, variable-speed wind generators, micro turbines, fuel cells, energy storage.

Source wise: Fuel cell / Battery; - Wind / PV.

AC-side: Grid coupling; - common (at least in one country).

    c. What is the inverter industry doing to address tomorrow's markets?

Answers:
They are actively pursuing emerging technologies. Unfortunately, they are still emerging (e.g., not yet a large fuel cell market).

Apply new technologies to inverters: e.g. new power electronic components (Cool MOS / IGBTs), new fast controller; e.g. DSP controller.

    d. Can larger inverter market segments serve new developing applications or does this violate economic rules?

Answers:
Subsystems and components from motor drives and UPS are relevant. Controls are not.

    e. Phantom Topic #3: What new markets are expected and how might these new markets affect future inverter designs and packaging for developing technologies?

Answers:
Energy security for military bases may direct development of off-grid interconnected sources (micro-grids). These will require energy storage to meet transient load requirements; hence, inverters.

Fuel cells – many more units will be connected to utility (higher density than PV expected.
New approach to anti-island technologies.

New strategies needed to operate these virtual power plants.

4. What is the common and disparate inverter needs by the different technologies (Solar, Fuel Cells, Micro-turbines, Wind, Storage, Automotive, Motor speed controls, etc)?

    a. What are the cost needs for each?

Answers:
Cheap. As each technology matures and becomes less expensive, the cost of the inverter will become more significant; for example, today the inverter cost is not a significant part of the cost of a fuel cell system (but can be a source of failures). Mature markets such as automotive have much tighter cost constraints.

    b. What are the performance goals for each?

Answers:
Performance varies by application rather than technology. Efficiency is more important where the dc source is expensive, as PV and fuel cells. Electromagnetic emissions are more critical in a sensitive environment such as a hospital or air-traffic control center.

    c. What are the reliability goals for each?

Answers:
It is probably more important to quantify time to failure for automotive and motor drives.

    d. What are the interface requirements for each?

Answers:
This is a key difference between motor drives and PV inverters. Motor drives interface directly to their motors/mechanical loads. PV inverters must regulate voltage and frequency to acceptable tolerances in standalone applications and must adhere to utility requirements in grid-tied applications.

    e. What are the common needs?

Answers:
Robust packaging that is tolerant of environmental extremes such as temperature and dust. EMI suppression so as not to interfere with or damage the microprocessors in a car. Power cycling. Surge capability.

    f. Phantom Topic #4: How can solutions to common requirements improve inverters for all applications?

Answers:
Basic switching bridge and robust packaging are applicable to both. Most important is manufacturing quality and automation, which are byproducts of large numbers/markets.

Inverter costs are not really power dependent BUT current dependent! Cost reduction only possible with higher voltages. Important issue: Overall system costs need to be optimized: String technology reduces costs for planning installation and improves monitoring capabilities of PV plants. Overall choosing the RIGHT System approach can reduce lifecycle costs!!!!!

5. What are US- and State- Government Program Requirements?

a. What research is needed?

Answers:
Most improvements can be made by application of state-of-the-art industrial engineering such as manufacturability, quality control, statistical failure analysis, modularity of control software, etc.

Thermal management simulation and analyses may be useful.

b. What funding will be required?

Answers:
Tremendous progress could be made both in understanding our present situation and in improving it with a fraction of the funding that goes into thin-film cell research.

A sustained effort of $5M/year could yield significant improvements if the program were properly technically managed.

c. Can this research and funding give US industry a market advantage?

Answers:
Without question. Refer to the success of SMA, heavily subsidized in Germany both by government installation incentives and support for its development.

d. Phantom Topic #5: Where is collaboration among the various DOE programs beneficial and how can it be coordinated?

Answers:
A fuel cell designer has told me that his job is to make dc electricity. Inverters are an add-on, an afterthought. This is exactly the process that has been followed in the PV program, wherein the overwhelming majority of the resources have gone to make dc electricity. Without a reliable inverter, there is no market for PV, fuel cells, energy storage, variable-speed wind, etc. A systems approach is critical for all these technologies to succeed.

Shall be answered by the American citizens.

6. What are “Inverter Manufacturing & Design Issues”?

   a. Manufacturing?

      i. Solder Joints?

Answers: YES, NO.

      ii. Circuit Boards?

Answers: NO.

      iii. Connectors?

Answers: YES (minimize); YES.

      iv. Integrated Assemblies (e.g., power supplies etc.)?

Answers: YES; YES.

      v. Power Electronic Packaging/footprints?

Answers: YES.

      vi. Heat Sinks?

Answers: YES (Thermal Management in General); NO.

      vii. Controls and Control Circuits?

Answers: YES - Big One (need common specs).

      viii. Transformers?

Answers: YES (magnetics can be improved); YES (inductors).

      ix. Capacitors?

Answers: YES (common failure point); NO (but for lifetime).

      x. Fans?

Answers: YES (avoid where possible - common failure point); YES.

      xi. Terminals?

Answers: YES (don't skimp here); YES; why are PV inverter terminal blocks so flimsy?

b. Power Electronics?

i. Thermal Management?

Answers: YES (major reliability issues); YES.

ii. Lifetime?

Answers: Needs definition; YES.

iii. Packages?

Answers: YES; YES.

iv. Integrated Bus?

Answers: YES; ???

c. Controls

i. Speed

Answers: YES, Most controls issues are low-speed. Protection must be high speed.
NO, may be needed only for future inverters with power quality improvements.

ii. Capabilities

Answers: Manufacturers are often asked for more than is required.
No, may be needed only for future inverters with power quality improvements.

iii. Universality

Answers: YES (standardize specs to reduce custom designs); YES.

d. Applications)?

i. Diversity?

Answers: YES (increase volume with common subsystems); YE.S

ii. DC side?

Answers: YES (surge protection, disconnects); YES.

iii. AC side?

Answers: YES (surge protection, disconnects, utility interface); YES

iv. Indoor Versus Outdoor Environment?

Answers: YES (heat transfer in hot climates, NEMA 4 desirable); YES.

e. Communications?

i. Can a universal communications protocol be developed?

Answers: YES, but functional requirements are more important - what is being communicated?

TECHNOLOGICALLY YES, but perhaps not in REALITY.

ii. What is the cost of including the communications within the inverter?

Answers: Negligible, but a liability if it leads to custom designs.
Depends on performance.

iii. Should communications be a separated function and cost?

Answers: Not necessarily - the first discussion should be requirements-until they are settled; this topic cannot be meaningfully addressed; YES.

iv. What customer friendly readouts and diagnostics are expected on the inverter?

Answers: Subject of great debate. Depends on application. Simple is better for residential market: red/green/yellow lights.

Indicate the Status of operation, energy yield, and performance in relation to neighboring system.

f. Environmental Issues

i. What is the recycle cost and is throwaway inverters or inverter sections a reasonable alternative to extremely rugged and long-lived (also costly) inverters?

Answers: Inverters that last longer than about 5 years will probably always be thrown away just as appliances are. Still, it is worthwhile to extend that time. Cost/benefit analysis needed of achieving lifetimes much greater than 10 years.

NO – Too expensive!

ii. What are the environmental impacts of shortened inverter lifetimes?

Answers: Negligible.

What about the goal of sustainability?

iii. How do you properly dispose of an inverter?

Answers: Solder from printed circuit boards is about the only hazardous waste, so it is similar to disposing of a TV.

g. Noise?

i. Is audible noise a problem?

Answers: Depends on location – Indoor and residential definitely an issue. Modern high-frequency inverters are quiet. Fan noise can be a problem - use high quality fans.

NOT with IP65 and switching frequency higher than 20 kHz.

ii. Can audible noise be economically reduced?

Answers: YES (see above).

NOISE NO PROBLEM with IP65.

iii. Is it economically feasible to produce different inverter packages with various noise ratings?

Answers: Not needed; NO.

iv. Where must noise be considered?

Answers: Residential; NOT WITH IP 65.

h. Consumer Concerns or Wants?

i. Costs

Answers: System cost will drive inverter costs: YES.

ii. Packaging

Answers: Small and unobtrusive.

iii. Displays

Answers: Simple lights with optional power readout at most; YES.

iv. Noise

Answers: Quiet (not noticeable); YES.

v. Heat

Answers: No hot spots in the garage.

vi. Warnings and Alarms

Answers: "Not generating-normally on at night", light plus possibly one general "call for service" light.

YES

i. Plug and Play
   i. DC interface

Answers: No custom voltage matching. Safety disconnects.

YES, but "END CONSUMER" NO!

   ii. AC interface

Answers: Minimal custom wiring. Use existing panelboard for grid-tied.

YES, but "END CONSUMER" NO!

   iii. Communications

Answers: Optional; YES.

   iv. Automatic or Manual Adjustments for Technology

Answers: Depends on application. Residential only if using stand-alone with batteries need to optimize for battery type to extend life.

Large grid-tied utilities may wish to adjust trip levels to coordinate with other protection.

YES.

   v. Code Compliant

Answers: YES; YES, YES!

j. What is Phantom Topic #6?

Answers: Can the government effectively support meaningful improvements in inverter manufacturing quality? YES!

Appendix C -
Final Agenda for the DOE Workshop for a Systems-driven Approach to Inverter Research and Development

Objective: This workshop is a follow-up to the systems driven approach workshop on solar energy held in December 2002. Participants will explore similar methodology for a new generation of inverters for PV. Initially, we will establish a baseline understanding of current inverter status. We will then examine factors influencing efficiency, reliability, cost, maintenance, manufacturability, and cross-technology applications. Potential R&D targets and tradeoffs will be addressed. A 5-year plan for inverter R&D is expected as a by-product of this workshop.

8:00 – 8:30 Sign-in, Breakfast Buffet

8:30 – 9:00 Outline of Systems Approach, Guidelines for the Workshop, Conceptual Framework Applied to Inverter Issues (Ray Sutula)

9:00 – 9:30 Vehicle Technologies Model Demonstration (Terry Penney)

9:30 – 9:45 Questions, Answers, Discussion (Dennis Fargo)

9:45 – 10:15 Inverter and Power Electronics (Stanley Atcitty/Ward Bower) *[State of the Art? Major markets? Current cost/performance? Latest research? Cost and performance targets vs. current status?]*

10:15 – 10:30 Questions, Answers, Discussion (Dennis Fargo)

10:30 – 10:45 Break

10:45 – 12:30 Inverter User Requirements *[Participants will have hard copies of presentations before the workshop and should be prepared for discussions and comments in advance of the workshop.]*

- 10:45 – 11:00 Photovoltaic Inverter (Michael Johnston)
- 11:00 – 11:15 Fuel Cell Inverter (Ken Krastins)
- 11:15 – 11:30 Electric Vehicle Inverter (Jon Lutz)
- 11:30 – 11:45 Micro-turbine Inverter (Capstone?)
- 11:45 – 12:00 Energy Storage Inverter (Ray Hudson)

12:00 – 12:30 Audience participation (Moderated by Dennis Fargo)

12:30 – 1:30 Lunch, Buffet Style

1:30 – 2:30 DOE Inverter R&D Programs

1:30 – 1:45 Solar Program (Dan Ton/Alec Bulawka)

1:45 – 2:00 DER, Storage Program (Imre Gyuk)

2:00 – 2:15 SBIR Phase II Storage Inverter Report. (Paul Duncan, AiraK)

2:15 – 2:30 Office of FreedomCAR and Vehicle Technologies Advance Power Electronics Overview (Bill Kramer)

2:30 – 2:45 Audience participation (Moderated by Dennis Fargo)

2:45 – 3:00 Break

3:00 – 3:15 Oakridge National Lab Inverter Design Issues (Don Adams)

3:15 – 3:30 Inverter Manufacturing Research under DOE PV Manufacturing R&D Program (Dave Mooney)

3:30 – 5:00 Audience participation (Dennis Fargo) *[Moderator will ask questions for presenters, mainly on points of clarification, 10 minutes. Moderator will then ask for comments on the information presented. Additions/comments will be recorded into a PowerPoint presentation format for audience.*

5:00 Adjourn

DAY TWO

8:00 – 8:30 Breakfast Buffet

8:30 – 8:45 Review of Day 1, Working Group Assignments (Moderator)

8:45 – 9:15 University Perspectives on Inverter Development (Dushan Boroyevich, Virginia Tech)

9:15 – 9:30 Preparatory for Breakout Sessions

9:45 – 10:00 Break

10:00 – 12:00 Facilitated Breakout Groups

WHAT IS NEEDED?

Group 1: High Reliability Inverter Requirements *[select a reporter for each group]*

10:00 – 10:45 Brainstorming session on characteristics of the inverter driven by:

1. Markets and Applications
2. Systems and Subsystems
3. Components, Materials and Processes

Participants will have been cued on the topic of discussion beforehand. Group will then decide what characteristics are important from a market-driven perspective. Issues to consider:

- o *Utility-integrated vs. stand-alone capabilities*
- o *Plug and play capabilities/modularity*
- o *Thermal management*
- o *Environmental considerations (i.e., indoor vs. outdoor installation)*
- o *Recycling and Upgrade Capability/disposal*
- o *Consumer concerns (Noise, readouts, etc)*

10:45 – 11:30 Correlating characteristics with research targets for:

- System Lifetime/ MTBF/ MTFF
- Costs
- Efficiency
- Other?

11:30 – 12:00 Summarize Results of AM Session *(*Moderator will then summarize research targets discussion.)

Group 2: Low Cost Inverter Requirements *[elect a reporter for each group]*

10:00 – 10:45 Brainstorming session on characteristics of the inverter driven by:

1. Markets and Applications
2. Systems and Subsystems
3. Components, and Materials and Processes

Participants will have been cued on the topic of discussion beforehand. Group will then decide what characteristics are important from a market-driven perspective. Issues to consider will include:

- *Utility-integrated vs. stand-alone capabilities*
- *Plug and play capabilities/modularity*
- *Thermal management*
- *Environmental considerations (i.e., indoor vs. outdoor installation)*
- *Recycling and Upgrade Capability/disposal*
- *Consumer concerns (Noise, readouts, etc)*

10:45 – 11:30 Characteristics with research targets for:

- System Lifetime/ MTBF/ MTFF
- Costs
- Efficiency
- Other?

11:30 – 12:00 Summarize Results of AM Session. (Moderator will then summarize research targets discussion.)

12:00 – 1:00 Lunch

1:00 – 1:30 Breakout Group Interim Reports – Main Room

1:00 – 1:15 Breakout Group 1 Interim Report
1:15 – 1:30 Breakout Group 2 Interim Report
1:30 – 2:30 Breakout Groups Continued

WHERE TO GO FROM HERE

Group 1: High Reliability Inverter Requirements

What are the key factors that need to be modeled for?
Markets and applications of inverter technology

Systems and subsystems used in applications,
Key components, processes, and materials,
The inverter package,
Other

Group 2: Low Cost Inverter Requirements

What are the key factors that need to be modeled for?
Markets and applications of inverter technology
Systems and subsystems used in applications,
Key components, processes, and controls
The inverter package,
Other

ASSEMBLE GROUP REPORTS

2:30 – 2:45 Break

2:45 – 3:30 Final Group Reports
2:45 – 3:00 Group-1 Report
3:00 – 3:15 Group-2 Report
3:15 – 3:30 Discussion, and the need for follow up.

3:30 Adjourn

Appendix D - Glossary of Terms

[1] ***Application Specific Integrated Circuit (ASIC)***	A highly integrated circuit package containing hundreds of logic functions that is modified by burning-away internal paths to produce application specific circuit functions. ASICs are used to provide design flexibility and to reduce cost and parts count in the control section of an inverter.
[2] ***AC PV Building Block***	A complete, environmentally protected photovoltaic modular system consisting of a PV module, a complete integrated inverter enclosed with a housing eliminating exposure of any dangerous voltage and generally doubling as the module frame or mounting structure that also encloses all of the necessary ac bus work, interconnects, communication, surge protection and terminations.
[3] ***AC PV Module***	A complete, environmentally protected photovoltaic unit consisting of PV cells, optics, inverter and other components designed to produce ac power when exposed to sunlight.
[4] ***Bi-directional inverter***	An inverter that can be operated in all four quadrants of the voltage/current regime hence may function as an inverter or as a rectifier by applying the proper drive signals. Power flow may be in either direction.
[5] ***Converter***	A general term used to describe a device for changing direct current power to alternating current power or vise versa or from one frequency to another.
[6] ***Current-controlled Inverter***	An inverter designed to convert dc power to ac power where the output current is controlled and unaffected by output voltage fluctuations. Typically used in utility-interactive applications where voltage is controlled by the utility.
[7] ***Electromagnetic Interference or Compatibility (EMI/EMC)***	Generally refers to electromagnetic interference (radio frequencies) produced by a device and electromagnetic compatibility (EMC) of the device. Inverters must not emanate excessive EMI or be susceptible to normal EMI. EMI may be radiated as a radio wave or conducted on the ac and dc lines.
[8] ***Emitter-Turn-off Thyristor (ETO)***	A new solid-state switch consisting of a thyristor device under development that is configured to facilitate device turn-off via emitter signals and generally switches faster than the commercial GTOs and can handle more power than IGBTs.
[9] ***Field-Effect Transistor (FET)***	A solid-state device that uses a voltage field to control the current flow through it. Devices used in today's inverters are usually metal-oxide-silicon FET's (MOSFETs) and are generally used when the dc voltage is less than 100V. They can easily be wired in parallel with each other to increase the current/power rating of the inverter.
[10] ***HALT***	Highly accelerated life tests that are conducted in a manner to reveal component and package layout weakness that have been related to premature failure mechanisms and mean-time-to-first-failure (MTFF).
[11] ***Insulated Gate Bi-polar Transistor (IGBT)***	A solid-state switch that combines the advantages of the FET and a bi-polar transistor. It requires low control power but has the advantages of low losses when in the "on" state. IGBTs are generally used when input voltages are greater than 100V. IGBTs have a wide range of capabilities and are now being integrated with built-in drivers and self-protection.
[12] ***Inverter***	A device designed to convert dc power to ac power. Inverters are also commonly referred to as power conditioning systems and power conditioners in photovoltaic applications. Inverters are often referred to as static power converters (SPC) in standards documents. The boundaries of the inverter were discussed extensively In this workshop, but it was not determined if the inverter included all disconnect switches, communications options, transformers or ground-fault detection/interruption.
[13] ***Line-Commutated Inverter***	An inverter designed to be attached to the utility grid or other ac source that requires the switch current to pass through zero in order to turn the switching devices "off." Several versions of small, single-phase, line-commutated inverters were used early in the photovoltaic program. Line-commutated inverters are still used for some three-phase intermediate-sized and all large (>500 kW) inverters.
[14] ***Maximum Power Point Tracker (MPPT)***	Circuitry associated with utility-interactive inverters (and some larger stand-alone) that continuously adjust the dc operating point to obtain the maximum power available from a photovoltaic array at any given time.
[15] ***Modular Inverter***	An inverter design that is compatible with paralleling or summing with one or more inverters of the same or similar design.
[16] ***Multi-level Inverter***	An inverter using a circuit topology that switches segments of the energy source in and out of the output circuit in order to synthesize a current sourced low frequency (typically 50 or 60 Hz) sine waveform.
[17] ***Non-Islanding Inverter***	An inverter defined in IEEE 929 as one that will cease to energize the utility line in 10 cycles or less when subjected to islanded loads that are > $\pm$ 50% mismatch to inverter real power output and power factor is less than 0.95. Alternatively, a disconnection from the line is required within 2 seconds if the load to inverter match is <50%, the

	power factor is >0.95 and the quality factor is 2.5 or less.
[18] ***Pulse Width Modulated (PWM)***	A method used in self-commutated inverters to generate a synthesized waveform (e.g. a 50 or 60 Hz sinewave) through a combination of varying the duration of time that the switches in a bridge are turned "on" and "off." PWM switching frequencies may be constant or vary. PWM offers the advantages of using high-frequency transformers and much smaller filter components. PWM frequencies may range from 5kHz to 100kHz for photovoltaic inverters. Many utility-interactive inverters use PWM.
[19] ***Self-Commutated Inverter***	An inverter that uses switches and controls that may be turned "on" or "off" at any time. Generally this inverter uses a PWM method to generate a synthesized waveform. Self-commutated inverters may be utility-interactive or stand-alone. They may be voltage controlled or current controlled.
[20] ***Silicon Controlled Rectifier (SCR)***	A semiconductor that is a member of the thyristor family. It cannot be switched from "on" to "off" with gate controls unless current through it passes below a holding threshold (typically through zero). These devices are typically used in line-commutated inverters.
[21] ***Static Power Converter (SPC)***	Terminology used in some standards for any static power converter with control, protection and filtering functions used to interface an electric energy source with an electric utility system. Sometimes referred to as power conditioning subsystem (PCS) or power conditioning units. Typically sold as inverters for photovoltaic applications.
[22] ***Stand-alone Inverter (S-A)***	An inverter designed to operate with the loads connected directly to its output and independent of any other ac power source. This inverter requires a battery at the input to provide dc voltage regulation and surge currents. The stand-alone inverter provides frequency and voltage regulation, overcurrent protection and surge capabilities for the loads. The S-A inverter must be a self-commutated, voltage-controlled inverter so that loads can be operated within their specified voltages.
[23] ***String Inverter***	An inverter designed to use a single photovoltaic string of modules for its input. The ac output of many inverters can be combined and fed to a common transformer. String inverters can be used to reduce dc wiring and protection costs and to improve redundancy of a large system.
[24] ***Thyristor***	A term used for a family of semiconductor switching devices characterized by bi-stable switching (either "on" or "off") through internal regenerative feedback. Some thyristors can be forced to turn "off" but many will turn "off" only when current through it falls below a holding current threshold.
[25] ***Transistor (Bipolar Transistor)***	A semiconductor device characterized by output current that is dependent upon an input current. They exhibit low forward losses but require more drive power than FET's or IGBTs. Several early inverters used bi-polar power transistors as switching devices.
[26] ***Utility-interactive Inverter (U-I)***	An inverter designed to be connected to the utility grid or other stable ac source. This inverter does not require dc energy storage and usually incorporates a MPPT to maximize power delivered to the grid. It may be self- or line-commutated and may be voltage-or current-controlled. Non-islanding requirements now apply to U-I inverters in the US, some European countries and in Japan.
[27] ***Voltage-controlled Inverter***	An inverter designed to convert dc power to ac power where the output voltage is controlled. Typically used in stand-alone applications since the output voltage must be regulated within the inverter. Voltage controlled inverters are also used as utility-interactive where they employ a line-tie impedance to limit current flow between the inverter and the utility.