2022 PSMA POWER TECHNOLOGY ROADMAP

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Brij Singh, John Deere
Dc-Ac Inverters

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APEC Plenary Speaker

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Purpose of the PSMA

The Power Sources Manufacturers Association (PSMA) is a not-for-profit organization incorporated in the state of California. As stated in the papers of incorporation, the purpose of the Association shall be to enhance the stature and reputation of its members and their products; improve their knowledge of technological and other developments related to power sources; and educate the electronics industry, academia, and government and industry agencies as to the importance of, and relevant applications for, all types of power sources and conversion devices.

PSMA Mission

The PSMA mission is to integrate the resources of the power sources industry to more effectively and profitably serve the needs of the power sources users, providers, and PSMA members.

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Foreword

The 2022 Power Technology Roadmap further reinforces the theme of empowering the electronics industry. The power supply industry, despite the pandemic-related setbacks, continues to emerge from the shadows to play a leading role in the next phase of electronics industry evolution. We hope that you will find plenty of evidence and indicators that underline this assertion as you are perusing this edition of the PSMA PTR report. Like the previous PSMA PTR reports, this report is a result of the collaborative work by all-volunteer participants, who happen to be leading experts in their respective fields. As a result, this spectrum of valuable information brings different perspectives, but is tied together by common formats and templates that have crystallized over time. This report is unlike any other in the power technology industry and we hope the readers benefit from its many insights.

This is the twelfth Power Technology Roadmap. The first report was in 1994. The next report came out in 1997 and the cycle has been repeated every three years up to the 2009 report. As the report's influence has grown, the frequency of the report also increased to provide our members, and the industry as a whole, more timely updates. As a result, this roadmap report became a bi-annual effort, with editions published in 2009, 2011, 2013, 2015, 2017, and 2019. During the pandemic, it was decided to revert back to a three-year cycle, though the industry will continue to get more dynamic views of the future through the PSMA PTR webinar series.

The Power Technology Roadmap is one of the primary benefits of your company's membership in PSMA. Please share this copy with others in your organization. Additional copies of this report, or any other PSMA publications, can be purchased at www.psma.com or by calling the PSMA office. Non-members may also purchase copies of the report at www.psma.com or by calling the PSMA office.

Philosophy

Since its inception, the goal of the report is to review, comment, and capture power conversion technology and trends for the next two to five years. As the industry evolves, the emphasis of the report changes, while many of the tracked quantitative metrics are retained for the sake of consistency.

Traditional applications in computing, consumer, and telecommunications segments remain technology responsive; however, many emerging applications have power technologies at their core and are technology-driven. These include solar inverters, variable frequency drives, electric vehicles, and LED lighting systems, to name a few.

In technology-responsive applications, the end user is indifferent to the features or other details of the power conversion technology embedded within the product or equipment. However, they also recognize that (largely due to constraints imposed by physics), the power converters have not obeyed anything equivalent to Moore's law and hence, the power converter sticks out in the rapidly shrinking application. The end users would like the power converter to physically "disappear" without losing its contributions, which leads to the quest for smaller, denser, more highly-integrated power conversion solutions. In technology-driven applications, the power conversion systems can be immediately differentiated through their technology advances. In all types of applications, the technology and differentiation are subject to

cost constraints and regulatory environments. All face the industry competitiveness that drives smaller size, higher efficiency, and better electrical performance, while continuing to drive down the cost curve.

These requirements result in severe technical challenges in the design, manufacture, and even in the selling, processes. These challenges push us to strive for new levels of excellence in our respective businesses. We need better materials, better components, better solutions, better aligned innovations from the academic research communities, and more effective ways to manufacture and deliver them. Our interests are best served by taking a proactive stance; by anticipating these challenges and developing the technology required to meet them on or ahead of time.

It is in this spirit that the PSMA has been conducting these Power Technology Roadmap activities since 1994. Leaders from the key groups – supply manufacturers, component suppliers, end users, academic institutions, and power industry experts – contribute their views through a series of public webinar presentations. These are conducted throughout the year prior to publication, encouraging high levels of industry participation while gathering these important perspectives. The webinars cover a wide range of power conversion topics loosely grouped into Application Trends, Component Technologies, University Research in Power Electronics, and Power Supply and Converter Trends. This is combined with the efforts of volunteer working groups that analyze industry trends and ultimately produce the output that is this report. Altogether, the PTR generates a kaleidoscopic view of the future that provides additional insights every time the reader peruses it.

What's New This Year

The PTR report always strives to provide multi-dimensional perspectives to the growth and evolution of power conversion technology. After starting with predictions for four major product segments, the Application Trends and Emerging Technologies commentaries were added in 2011 and 2013, respectively. In the 2017 edition, a new chapter on Component Technologies was added.

Beginning with the 2019 edition, a new chapter on University Research in Power Electronics has been included. Major university research programs in power electronics were asked to provide a snapshot of their research priorities in the coming years and these inputs are presented and analyzed. This additional dimension was further strengthened in 2022 by much broader participation rate (28 universities compared to 14 in 2019). Also, from the 2019 edition; the Emerging Technologies chapter was merged into the Application Trends and Component Technologies chapters.

Significant changes were made in 2022 to the Power Supply and Converter Trends chapter. A new section addressing trends in dc-ac inverters was added, focusing primarily on traction drives for the rapidly growing electric vehicle (EV) market. To complement this new section, the dc-dc isolated section has added a category for high-power technology, focusing on the isolation stage in the on-board battery charger. The scope of the low power dc-dc isolated section is modified to cover product trends below and up to 100 W. The scope of the ac-dc front-end was also changed this year, expanding the range to 3000 W in recognition of an increasing range of high-power front-ends, driven in large part by changes in cloud and data center infrastructure.

Other than the above-mentioned changes, this year's roadmap follows the format of previous years' roadmaps and maintains the consistency of format and sub-sections.

In this pandemic impacted cycle, the PTR webinars maintained a consistent pace and momentum that served the power electronics community well and partly compensated for the missing in-person learning opportunities at industry conferences and workshops. As a result, the number of webinars presented rose to a record level of 22 during this cycle. We continue to include the recorded webinars on the digital copies of this roadmap report (on USB drives). The webinars add much to the presentation materials because the listener can hear and understand the context and the subtext of the original presentation in the speaker's voice. Including the recordings also allows us to capture the interesting and informative question and answer periods – which last as long as the webinar presentation in some cases, indicating high levels of active audience participation and fostering further learnings for the presenters and audience alike. We appreciate these interactive discussions and their contributions to how we understand our industry and the underlying power technologies. Sharing information and improving knowledge is, after all, the goal of PSMA.

While the roadmap report looks to the future for power technology trends, we should also be cognizant of what came before. It is not possible to include the content of all the previous roadmap reports, but recognizing the previous work and topics discussed shows the evolution of topics and trends. We provide a listing of the previous years' presentations and their authors in Appendix III.

The end result of all the webinars, surveys, and discussions is this report. It offers a consolidated view of the latest trends in the management, control, and delivery of state-of-the-art power conversion technologies. We hope you find it useful, thought provoking, and valuable.

Conor Quinn and Dhaval Dalal
Roadmap Chairs

Acknowledgements

The PSMA Power Technology Roadmap is a result of the collaborative work by volunteer participants.

We would first like to thank the webinar presenters, each of whom put many hours into the webinars. A large portion of the success of the PTR is due to their efforts in preparing the materials and their skills in delivering the information clearly and concisely. The willingness of all the presenters to answer questions posed by the audience brings additional value to the PTR effort.

Likewise, we thank the authors of the articles and summaries that bring together the Application Trends, Components Technologies, University Research in Power Electronics, and Power Supply and Converter Trends chapters of the reports. All of these authors are industry experts who have taken time to articulate their views of the major trends and challenges in each vertical application segment and the overarching technologies as they apply to power electronics.

Special thanks are warranted for the segment leaders whose efforts were essential to completing this report. Thank you to Brian Zahnstecher and Ed Massey (Ac-Dc Front-end Power Supply Segment); Stephen Oliver (External Ac-Dc Power Supply Segment); Mark Scott, Steve Roberts, and Matt Dauterive (Isolated Dc-Dc Converter Segments); Jeff Nilles, Xin Zhang, Arnold Alderman, and Ada Cheng (Non-Isolated Dc-Dc Converter Segments); Ralph Taylor, Brij Singh, and Thomas Foulkes (Dc-Ac Inverter Segment); Ajay Hari and Upal Sengupta (Application Trends chapter); Eric Persson (University Research chapter); Reenu Garg, Jaume Roig, Matt Wilkowski, and Tim McDonald (Component Technologies chapter); and Ritu Sodhi (APEC Plenary Speaker).

The report was further enriched by many other power technologists, component experts, and academics. They are listed in the appendices and their input provided the base for the quantitative power supply design trend tables; an essential part of this report. The segment leaders provided additional interpretation and summary excerpts and insights that complement the presentations and the tabulated survey results.

Laurie House again helped edit the full report and kept things together during another chaotic race to the finish line.

Finally, the PTR webinars and this report could not have succeeded without the help of Joe, Lisa, and John Horzepa of PSMA. John and Lisa did a great job arranging the meeting facilities, providing valuable feedback through the process, and managing the book printing and USB drive duplication process. We also thank the PSMA board of directors for their continued and steadfast support.

The PSMA Power Technology Roadmap continues to be published on two-year or three-year cycles. We hope that many of the existing and new volunteers will continue to support or join this extremely rewarding effort.

Conor Quinn and Dhaval Dalal
Roadmap Chairs

Chapter I
Roadmap Overview

Roadmap Goal

The goal of the Power Technology Roadmap is to paint a comprehensive picture of the direction of the power technology in the next two to five years. While it provides selective metrics to project the technology evolution and trajectory in quantitative terms, it contains significantly more valuable and potent qualitative information in the pages written by many leading industry experts.

The member organizations will benefit by using the report as a companion to the readily available market reports – which may contain more specific market projections, but lack the "why and how" behind those projections. The report is also intended to act as a "call to action" for the member organizations in terms of addressing the gaps in the ecosystem identified in the report.

Roadmap Methodology

The PTR 2022 activities started in March of 2019 in Anaheim, CA, at the 2019 Applied Power Electronics Conference and Exposition (APEC). During APEC, PSMA organizers held a kick-off where interested members attended a meeting to review the scope of the report. There was also a lessons-learned analysis of the just-released PTR 2019 report to facilitate learnings and improvements.

Like the previous roadmap, the report's structure remains a three-dimension overview of:

- Application Trends and Emerging Technology (which may be used across many products and are enabled by many components)
- Components Technologies (power semiconductors, ICs, magnetic materials, etc.), and
- Power Supply and Converter Products and Technologies (ac-dc front-end power supplies, external ac-dc supplies, isolated and non-isolated dc-dc converters, dc-ac inverters)

Figure 1 provides a 3D visualization of the power technology roadmap structure. The power technology roadmap cube ("PTR Cube" below) shows how each of the technology, component, and application segments intersect and overlap, describing the dependency between multiple cross segments.

Figure 1. The PTR Cube

The first Power Technology Roadmap Report in 1994 had products as its focal point and discussions of component technology and applications technology were framed in that context. Over the years, the scope of product coverage has expanded. This year, a new section on dc-ac inverters has been added and each of the dc-dc segments has been split or broadened in scope. Core teams were formed to analyze each of the following and produce trend tables and accompanying summary text:

- Ac-Dc Front-End Power Supplies (200 W – 3000 W)
- External Ac-Dc Power Supplies (up to 150 W, with data specific to 27 W and 150 W)
- Low-Power Isolated Dc-Dc Converters (up to 100W)
- High-Power Isolated Dc-Dc Converters (with a focus on electric vehicle chargers)
- Non-Isolated Dc-Dc Converters (traditional packaging)
- Non-Isolated Dc-Dc Converters (PSiP and PwrSoC)
- Dc-Ac Inverters (with a focus on electric vehicle traction drives)

The applications are the second facet of the cube and get their own dedicated chapter. Both applications and components were addressed through webinars from 2009, with the applications chapter introduced in 2011. Trends addressed in this cycle by application experts are as follows:

- Vehicle Electrification
- Cloud Computing
- USB Mobile Device Chargers
- Portable Power Tools
- Micropower Systems
- LED Horticulture Lighting
- Renewable Energy and Grid Storage

The component facet got its own dedicated report chapter in 2017 and the scope has continued to improve, addressing active, passive, and packaging aspects of components. In this cycle, the following component topics are addressed:

- IGBTs
- Low- and Mid-Voltage MOSFETs
- Silicon Super-Junction MOSFETs
- GaN Discretes (Low Voltage)
- GaN Discretes to Smart Power Circuits (High-Voltage)
- GaN Power ICs
- SiC Diodes and MOSFETs

- Isolated Gate Drivers
- Packaging in High Power
- Prismatic Aluminum Electrolytic Technology
- The Future of Magnetics
- Power Packaging and Manufacturing

Webinars help cover all three facets and add a "real-time" element to report updating. Participants and observers don't have to wait two or three years for the latest information. For this roadmap cycle, a series of webinars was conducted between February 2020 and December 2021, gathering perspectives and data from a broad range of experts representing component suppliers, research institutions, consumers of power conversion equipment, and companies that provide services to the power industry. These webinars presented snapshots of state-of-the-art in power conversion technology, synopses of end-customer expectations for the next few years, and perspectives on how component technology is changing.

In recent years, we have opened the webinars beyond PSMA membership to all interested parties, which has increased the participation level significantly. The webinars were generally an hour-long with a question-and-answer period that sometimes got extended with significant dialogue. This allowed the segment leaders to gain a more thorough understanding of the trends being discussed.

The webinars were recorded to allow the segment teams to review the presentations for estimating trends for each product. The recorded material is available as part of the electronic copy of this roadmap report. The webinar recordings add much to the presentation materials as the listener can hear and understand the context and the subtext of the original presentation in the speaker's voice.

To further complement all facets, a chapter covering university research was added in 2019 and this year's responses have almost doubled from the prior survey.

The Presentations

The roadmap cycle and this report include a total of twenty-two presentations loosely grouped into the four technology categories around which the report is structured.

Application Trends

- Powering and Retrofitting IoT Devices for Industry 4.0
- Emerging Energy Efficiency Regulations with Emphasis on EU EcoDesign and Energy Labeling
- GaN-Based Solutions for Cost Effective Direct and Indirect Time-of-Flight Lidar
- Broader Power Markets and Applications Enabled with Silicon Carbide
- Latest Trends in Vehicle Electrification from Semiconductor Perspective
- Trends in Battery Energy Storage

Component Technologies

- Utilizing WBG Devices in Next-Generation Power Converters
- JEDEC JC-70 Issues Industry First Guidelines for Testing and Evaluating Wide Bandgap Power Devices
- Accelerated High-Voltage GaN Reliability Testing and Advanced Switching Techniques for Improved Ruggedness
- Microprocessor Power Delivery – Decoupling Capacitor Challenges in the 2020s
- Traditional and Machine-Learning Based Magnetic Core Loss Modeling
- Next-Generation GaN Integration: Autonomy, Efficiency, Reliability

University Research

- Advanced Packaging Concepts for Wide Bandgap Power Electronics
- Ultra High Density Double-Sided Half-Bridge Packaging with Organic Laminates
- EMI Diagnostics – A Tool for Estimating Capacitor Health
- Energy Harvesting for Low-Power IoT Applications in Low-Speed Rotating Machinery
- SiC: Beyond Power Devices
- Physics-Based Modeling Approaches for Magnetic Material and Components

Power Supply and Converter Trends

- Test vs. Analysis – What is the Right Ratio for Achieving High Reliability
- How Data Science and Artificial Intelligence Can Help Power Electronics and Power Semiconductor Technologies
- Fundamentals and Application-Oriented Evaluation of Solid-State Transformer Concepts
- Coordination of Operation of a Future Power Network with Increase in Inverter-Based Resources

Summary of the Roadmap

Readers are encouraged to review the various chapters of this report and draw their own conclusions. With such vast data and diverse commentaries, it is near impossible for editors to distill the report down to a single-page summary. We have tried to identify the cross-currents and common themes among different chapters and presented those in a summary table below.

*Table 1. Webinar Cross Reference **

Webinar	Application Trends	Component Technologies	University Research	Power Supply and Converter Trends				
				Ac-Dc Front-End	Ac-Dc External	Dc-Dc Isolated	Dc-Dc Non-Isolated	Dc-Ac Inverter
Hari	✓	✓		✓	✓	✓		✓
Butler at al.		✓		✓	✓	✓	✓	✓
Hayes et al.	✓		✓				✓	
Schanen		✓	✓					✓
Barr et al.		✓		✓	✓	✓		
Chen, D.	✓			✓	✓			✓
Hopkins et al.		✓	✓	✓				✓
Glaser	✓	✓					✓	
Hill	✓	✓					✓	
Hymowitz				✓	✓	✓	✓	✓
Moxey	✓	✓		✓		✓		✓
Scott	✓	✓	✓	✓		✓		
Sarkar	✓	✓	✓	✓	✓	✓	✓	✓
Chen, M. et al.		✓	✓	✓	✓	✓	✓	✓
Kolar et al.	✓		✓	✓		✓		
Ramasubramanian	✓							✓
Bader	✓		✓					
Mantooth	✓	✓	✓	✓				✓
Cui		✓	✓	✓	✓	✓	✓	✓
Kinzer	✓	✓		✓	✓	✓		
Crisafulli	✓	✓		✓		✓		✓
Rohan	✓	✓						✓

(*) Somewhat subjective. There may be other less obvious relationships today or relationships that will develop over time as technologies mature.

In summary, we would like to highlight that this roadmap is unique in terms of it being fully a volunteer effort. As you read through the pages, gather insights, and develop questions; what better way to extend the tradition than to contribute to the next edition of the roadmap through your active participation?