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Photovoltaics R&D: A Tour Through the 21st Century

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PHOTOVOLTAICS R&D: A TOUR THROUGH THE 21st CENTURY

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ABSTRACT: The future investments for photovoltaics *research & development* are contemplated for this new millennium. Current technologies are used as the foundation for what might be expected for the next 50 years. A 'tour' is conducted through what we and our coming generations can anticipate for this technology—emphasizing non-conventional applications beyond the "expected". Next-generation research approaches are predicted indicating the horizon of PV technology. Conjectures of those PV and related technologies that are *beyond* this horizon are presented, with prognosis what our coming generations might have as *their* 'conventional' energy sources.
Keywords: Energy options -1: Fundamentals -2: Solar Cell Efficiencies -3

1. INTRODUCTION AND DESCRIPTION

For the past 50 years, *technology and globalization* have marked our lives—both setting the direction and propelling us into the coming century. United States President H. Truman advised us that *"the only thing about the future that you couldn't predict was the history you didn't know"*. This paper provides a prescriptive look at the future of technology—focusing on the future of photovoltaics technology—and the science and engineering strategies and targets needed for the impressive PV evolution foreseen in the coming millennium. Using Truman's insight, we will base parts of our insight into tomorrow's PV R&D based upon guidance of whence history has brought this technology and where we are positioned to begin our journey into the 2000s.

As a gauge, Fig. 1 presents a general representation of major techno-economic eras covering roughly the past 3000-4000 years, measured by impact and value-added in terms of technical, economic, and global significance. Such eras can be represented by "S"-shaped life-cycle characteristics, associated with 4 stages of a typical life cycle: *birth, emergence, maturity, and levelization/decline*. The levelization/ decline of an era does not mandate disappearance, but rather less significance compared to valued-added in terms of the indicated driving forces. For example, the *Agrarian Age* became overshadowed in terms of its value added with the coming of the industrial revolution and the rise of electronics, microcomputers, telecommunications, and the information superhighway. In general, the representations of the major eras are observed to become steeper (more impact) and shorter in duration. While the Agrarian age covered many 100s of years, the Industrial Age is typically confined to ~200 years. The *Information Age*, which is just reaching its final life-cycle stage, is 40-50 years—starting essentially with the discovery of the transistor. If such generalizations of the past are sometimes disputed; predictions of future eras and what will be contained within them is risky at best—although for specific technologies like photovoltaics, their credibility or dismissal will be more concrete than the Oracle of Delphi or Nostradamus!

We are now embarking into the *Ages of Materials, Biotechnology, Nanotechnology, and Neoteric Energy*. Though somewhat discipline-diverse, they are the direct or indirect drivers for our PV R&D in the new century. In simple terms: to biotechnology and nanotechnology, we will be a contributor and enabler; to materials, we will be a major beneficiary, as well as benefactor; and to neoteric energy, we will be a leader. PV, as a successful business, will continue to be guided and enhanced by its R&D competencies. In turn, photovoltaics science and engineering will couple with each of the major designations in the coming ages—the empowering a new society in the 21st century.

A tour into the coming millennium (or a photovoltaic overlay to the coming Ages defined in Fig. 1) would profit from a map—something to provide assistance in choosing the routes, validating the mileposts or interim points of interest, and establishing our destination(s). Several such "long-term planning and strategy" maps exist—with a common feature of charting growth for the PV technology. We will use portions of the recently developed **U.S. PV Industry Roadmap**, which serves as an independent guide for U.S. PV research, technology, manufacturing, applications, markets, and policy—through 2020 (and beyond). This roadmap goal is to open U.S. markets and serve international ones, with a U.S. contribution exceeding 6 GW_p in 2020, and a U.S. installed (cumulative) capacity of 30 GW_p over this period, with the price of PV to the user of \$3/W (AC system, including O&M costs) in 2010 and approaching half that in the next 10 years. The expectation is that the U.S. markets will grow primarily in distributed (grid-connected) generation and value (AC and DC) applications, accounting for about 85% of the PV installations in the U.S. in the period 2010 through 2020. The requirement for the PV industry is represented in the growth characteristics of Fig. 2. The roadmap target is an aggressive 25% annual growth. Comparisons to 'business-as-usual', accelerated, and other scenarios are also represented. In any case, these "roadmap endpoints" provide a guiding framework for this tour into the photovoltaics R&D future.

2. PV R&D: THE TOUR*

Photovoltaics research and development in coming century is addressed in three temporal segments, dividing the century into the immediate term (2000-2015), the intermediate term (2010-2025), and the far-term (2020-2050 and beyond). Each of these segments will identify R&D pursuits that address the endpoints of the roadmap—as well as the predictions of the global, economic, and technical values dominating the ages in the 21st century (Fig. 1). Specifics are summarized in Table I, which provides a quick examination of the PV R&D associated with each of these periods.

* *The emphasis of this tour is PV materials and device R&D, although it is necessary to show relationships to the technology development and growth to show relevance, timeliness, and relationships. It is equally acknowledged that research in other areas (e.g. BOS, storage, systems, etc.) is of importance to the success of this technology.*

2.1 PV Technology 2000-2015: Period of Enlightenment and Revolution

This immediate period of PV R&D will be known for closing gaps between existing and predicted performances for both research devices and manufacturing components. The *enlightenment* will come from the achievements in understanding the science and engineering that limit performance. The *revolution* will arise from the successful application of this understanding, leading to not only the real improvement in current technologies toward their theoretical levels, but also to the demonstration of novel approaches, structures, and new materials that will form the basis for the next-generation of PV technologies. There will be a push (insistence) for following new technology paths and lessening the time between technology demonstration and commercial introduction. This will be a critical period for PV because it will set the stage (the technology competency) for what will come, while at the same time establishing consumer confidence in the current PV products. Laboratory R&D highlights will flood all PV technology areas. Crystalline Si cells will exceed 25%, thin-Si (less than 30 µm) will approach 20%; compound semiconductor, thin-films will demonstrate 20% efficiencies early—setting the stage for multijunction approaches with >25% efficiencies. Concentrator cells will continue their rebirth, with 35%, 2-4 junction cells verified by 2005, and >40%, 3-4 junction devices by 2010 (under concentations of 1000x). There will be an intense revived interest in new materials, cells designs, and approaches. Geometric and geomantic approaches to cell designs will offer new potentials for performance optimization, especially maximizing photon collection under real or special operating conditions. Organic semiconductors will receive new scrutiny, leveraging successes in the LED, display, and detector technologies. Nanoparticles and nano-engineered semiconductors/interfaces will build into a new device physics area—buoyed by impressive laboratory demonstrations of cell potential. There will be a surge in thermophotovoltaics interest—due largely to applications in the industrial environment and use with fossil fuels—and new thin-film TPV R&D will start to dominate this technology. Hydrogen research will become more closely aligned with the photovoltaics technology. First, there will be a linkage between PV and hydrogen as a storage option. This will include R&D on combinations of solar cells with various advanced storage concepts, focusing on such novel materials concepts as nanotubes, fullerenes, porous media (e.g., silicon), membranes, organic materials, and non-structured materials. Second, there will be a rebirth of research on hydrogen and simple molecule production using photovoltaics (including some new concentrator designs) to break water (primarily but also other liquid/viscous matter) into hydrogen and remaining components. This research will provide technology paths toward self-contained systems providing water (for hydrogen and oxygen use, consumption), hydrogen (for energy storage, fuel, and other energy conversion), as well as primary electricity. Synergistic requirements will unite diverse disciplines from chemistry, physics, engineering, and systems in realizing working laboratory prototypes.

The *new chemistry* will begin to dominate R&D approaches to rapid materials/device optimization, invention, screening, and exploration. Combinatorial approaches will be routine in the R&D and indus-try laboratories to experimentally find the right compositions, unmask the correct processes, and create and screen libraries of combinations of alloys, cermets, and compounds with exceptional, novel, or extraordinary properties for potential PV use. This will mandate the integration of computational screening procedures, robotic handling techniques, and special characterization approaches. There will be parallel advancements from the co-important analytical and measurement sciences. Major changes and contributions will come from theory—which will finally provide guidance instead of justification; direction instead of diagnosis, and sound prediction to enhance mere explanation. Foremost in this area will be the development and refinement of modeling techniques to predict new materials and structures with exact requested properties—*designer photovoltaics*. Using first-principles approaches, clever algorithms will be developed to rapidly forecast binary, ternary, and quaternary structures (with exact atom locations) for validation by the experimental materials scientists. This will lay the groundwork for future developments in the materials/device engineering arena for PV. This approach is the inverse of the experimental combinatorial methods, but provides a complementary and competing approach to materials development. Measurements and characterization will continue to evolve to answer and anticipate technology needs, with emphasis on greater accuracy/precision, greater spatial resolution, capability to non-intrusively probe large cell areas, and development of novel, in-situ diagnostics for the research and manufacturing-line environments. Device modeling will be integrally coupled with measurement science for guiding cell development with real parameters, real devices, real results. Throughout the century, these functions will continue to anticipate PVR&D needs, providing requisite guidance, support, and validation. This research era will highlight *knowbotics*—using software agents (knowledge robots) to efficiently, rapidly, and accurately sort though masses of available information and advice for materials and device development. These agents will not only save time, but eliminate unnecessary duplication in the R&D environment.

Space PV will receive added interest and importance due to the proposal and initial introduction of new, private sector extraterrestrial investments. Communications, global positioning, scientific, and government (including military) applications will continue growth. However, the first applications for 'private citizens' (high-end vacations, therapeutics) and 'unique manufacturing' (pharmaceuticals and biologicals with properties only practicable in space environments) will be realized late in this period. These will demand the start of huge manufacturing capabilities for space device designs that will both enhance the photovoltaic industry growth (adding as much as 10 GW/year by 2010), bring consumer confidence in the technology, and provide for new research capacities for PV that will strengthen development of terrestrial products (leveraging). The *future* and *emerging* portions of the S-curves for the biotechnology lifecycle herald the emergence of R&D and growth in PV manufacturing to meet the demands for these 21st century businesses.

During this period, there will be some decisions made on PV approaches—but the multitude of new and exciting technologies will greatly expand the research horizon. Silicon will continue to be the major PV resource during this period, but: (1) Si devices will evolve into thin layers and thin films; single and multicrystalline will start to be replace by poly-, micro-, and nanocrystalline categorizations.; and (2) polycrystalline (with 15% modules) and amorphous thin-film technologies will emerge as major players in the market—spurred by building integration architectural applications, and lightweight, portable applications. The latter of these two shifts will both be make possible by the significant R&D push and contributions, and will, in turn, fuel further evolution of these technologies.

2.2 PV Technology 2010-2025: Period of Evolution and Expansion

In this intermediate-term, the performances of PV components will be pushed to and beyond their preconceived performance ceilings through the development of non-conventional approaches to the technology. While the PV industry is undergoing impressive growth, R&D will evolve rapidly in both established, reborn, and new technologies. Photovoltaics research will be characterized by its greatest period of expansion and achievements. New performance goals will be established and new/novel approaches to photovoltaic conversion will lead to new baselines for R&D. Based upon the successes in the previous period, PV is accepted as a viable energy source. The expansion of the PV industry worldwide provides a window of opportunity for investigating new concepts. The PV processing line will be rich with its inheritance from its fundamental and applied research resource. Multi-sensory robotics, *knowbotics*, intelligent processing, advanced simulations, computer integrated manufacturing, in-situ diagnostics/controls, advanced expert systems, statistical processing—coupled with neural networking (allowing the manufacturing system to learn and adjust from past experiences)—mark the entry of PV into *21st century manufacturing*. The redefinition of quality will put added weight on the R&D community for more advances with the principle: *if it works, it's obsolete*. R&D will be tasked to deliver the <u>next</u> generation of technology even for the <u>current</u> generation of consumers. Photovoltaic research directions will be coupled with and complemented by other technologies, especially *biotechnology, nanotechnology, and materials*. This period owes its inception to the successes of the first 10+ years of the century; in turn, this time is critical to elevating PV into full technological acceptance and prosperity. The PV industry will focus on and profit from *products that sell*; the flood from R&D of new devices, concepts, and processes into the manufacturing environment will multiply that population of *product that sells*.

The previously classified "non-conventional" will become viable, prevailing technology considerations. New concepts will continue to filter generously into the research environment. Solar cell-hydrogen systems will be introduced for chemical production and storage. There will be a surge of experimentation and validation of new PV materials. This will build upon the theory/modeling established in the earlier period. Laboratory synthesis systems will 'build' (layer by layer, atom-by-atom) PV-designer materials within hours, using the direct input of the theory-predicted 'best' PV possibilities. Organic semiconductor cells will demonstrate performances nearing 10%. Nanomaterials will emerge: nanoparticle, nanoscale, and molecular devices with exceptional performances (e.g., quantum dots having efficiencies 2-3 times those for conventional PV, nanoscale rectifiers for conversion of noise spectra; quantum antennas for cosmic noise conversion; atomic engineering of interfaces and devices with optimized PV properties).

Nanotechnology will contribute new applications and new enabling technologies for PV. Integration of PV into micro-electronics and biological environments will become common. Micro-mechanical machines, including 'generators', with integrated PV power packs will focus interest in this new area of science. Nanomachines, using room-temperature superconductors for storage and charged by integrated PV, will find use in biological and electronic technologies. Supercomputers and other electronics will us PV integrated power sources. The "wide-application" life-cycle period of biotechnology, for example, will owe a good portion its huge success to the availability and technology of PV for space—the business opportunities introduced late in the previous period. This period will mark the huge growth of PV manufacturing specifically for these extraterrestrial PV markets—large-scale power, "big PV." Biotechnology will herald a surge in interest and investigation of photovoltaics for diagnostic and biomedical devices ("small PV", with extremely high value). Considerable work will also be directed toward the replication of biological systems in the light conversion—*biomorphic designs*. This bioreplicating will center on mimicking nature's functions, fashioning them into efficient conversion devices. This will include photosynthesis, photochemistry, photolysis, photokinesis, phototaxis, photorespiration, photophosphoylation, photomorphogenesis, photoautotrophogenesis—and a host of other light-stimulated events in biological units. Solid-state and electrochemical equivalents will be improve on nature's inherent light-excited processes into energy conversion and storage mechanisms.

This period is one underlying factor in the birth of the Age of Neoteric Energy. Large populations will start to depend on photovoltaics on earth and extraterrestrial for electricity. It is the demarcation between minor and major, between, novelty and reality, between skepticism and acceptance, and between poor and profit for PV in this escalation of clean, competitive energy integration into the world's arsenal of generation capacity.

2.3 PV Technology 2020-2050 (& Beyond): Period of Establishment, Contribution, and Prosperity

In this longer timescale, PV will be producing, selling, and installing multi-terrawatts of clean, competitive, needed electricity for consumers and applications worldwide. The global industry will reach 10s of GW annual production levels early in this period—but new PV approaches will continue to enter the marketplace. R&D cannot become complacent. Rather, it must be the battleground in exploring new technologies for the yet coming generations of electrical production needs. PV will be a *power of choice*, but the competition in the energy mix, and demands of the global and extra-global economies will provide fertile fields for technological nurturing and growth (a new, long-lived "PV agrarian age"). Research will continue to lead and guide energy development, although we will now have exposure to dramatically different approaches, technologies, and sources about which we have not yet even dreamed. New physics will unleash new technologies. This will (finally) be the time of <u>genuine</u> <u>breakthroughs</u> in photovoltaics research and technology development.

New materials and compounds will continue to be a focal point of fundamental R&D, both search and synthesis. New reserves, possible new compounds/elements, naturally occurring, pure semiconductors will emerge from non-terrestrial sources. Space exploration in the mid-to-late 2000s will begin to uncover resources that will lower PV materials costs, provide impetus to look at approaches previously thought to limited by material abundance, and provide the beginning of manufacturing both in space and possible other-than-earth environments.

While conventional PV will continue to drive the industry for economical power generators leading the neoteric energy—medical science will enable a niche for high-impact, value-added PV applications. One could imagine implanted diagnostic probes for monitoring/sensing, utilizing low-power sources or integrated "TPV' type converters "tuned" to the radiation spectra of internal body environments. Such converters might also be used to power nanoscale transmitters for wireless transfer of data from inside the biological system.

The descendents, distant relatives, marriages, and acquaintances of photovoltaics will lead to whole new energy conversion technologies that were not on the drawing board or in the scientific minds during the first decades of this century. "New physics" will sprout new schemes and new research directions. "Old approaches" will have reached ultimate performances in commercial products. There will be a "rebirth" of approaches that could not be pursued earlier because the physics and technology to realize these approaches was just not available at the time they were proposed or originally investigated.

3. THE LOOK FORWARD

By the end of this century, photovoltaics will not be what we know today. Our great-great-great grandchildren (both real and scientific!) will be looking at the 1999 single-crystal, multicrystalline, thin-Si modules, and our current advanced designs in the "Techno-Antiquities" section of their holographic cyber museums (perhaps even remote viewing such events)—much as we today are enthralled and a bit amused by the Model T Ford (1909), the first airplanes (1902-4), the Bell Labs transistor (1940 and the Si solar cell (1954), the first "single-crystal Si modules" (1956), the first integrated circuit (1959), or the first personal computers (1979-81). Our work (like these 20th century advances) will be described as "pioneering", "foundational", "visionary", "struggling", "clever", "risk taking", "ingenious", "champion"—but (with a consideration of current technology) "simple", "unsophisticated", "limited by the physics of the time", "bulky", "old-fashioned", "rudimentary", "low-tech", and certainly, "under funded"! What we are doing now is certainly providing the route, the right direction, for the success of photovoltaics in the coming century, not the final destinations/solutions. Our technologies are making possible the technologies of tomorrow—even though those technologies will certainly only remotely resemble in the year 2099 what we cherish and are consumed with today! We may only partially see the benefits of what so many have struggle to provide with our technology as over the past year, 10, 20, or even 40 years. However, to change Truman's words a bit *"the only thing about the future that you can predict is the history you know must come"*. Photovoltaics will not only survive and evolve, it will prosper and lead, through the Age of Neoteric Energy—and beyond.

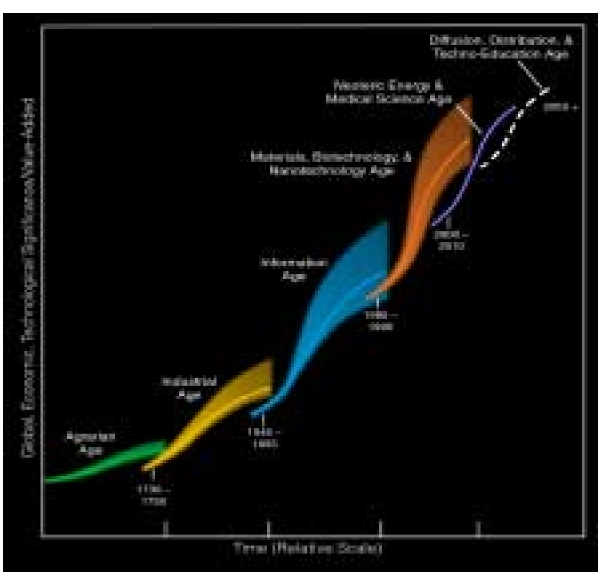

Figure 1: Major techno-economic eras on a relative time scale.

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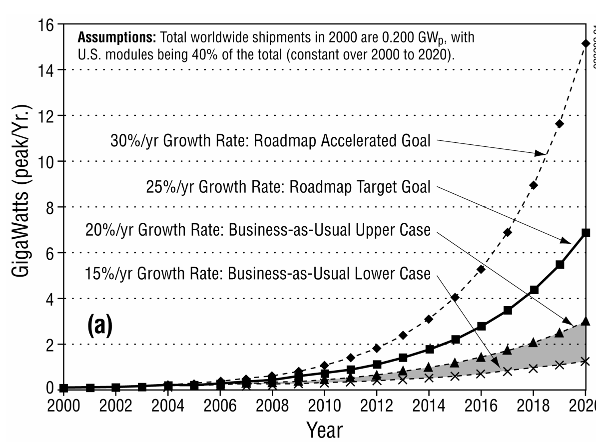

Figure 2: U.S. Industry Roadmap Growth curves.

Table I: Summaries of developments for various ages and periods.

Period of Enlightenment and Revolution 2000-2015	
Key: E-early in period; M-mid period:	L-late in period
Improvement in Existing (primarily 20th Century) Technologies	
	Crystalline Si cells exceed 25% [M] Thin Si (<30µm) exceed 15% [E] approach 20% [M] Polycrystalline thin-film (CIGS, CdTe) validated at 20% [E] Multiple-junction amorphous cells validated at >15% (stabilized) [E-M] Concentrator cells: • 35%, 2-3 junctions [M] • >40%, 3-4 junctions [L] Modeling coupled with actual device realization [E-L] Combinatorial optimization approaches to materials and device development: R&D procedure of choice, with rapid screening, scanning tools and characterization [E] "Knowbotics" (*encyclopedic agents* for effectively searching/sorting/identifying properties- and archetype characterization for modeling needs) Space cells: new designs and demonstration of multijunction crystalline (30% AMO) and thin films (20-25% AMO) [E-L] Measurements (evolve anticipating technology needs) [E-L] • greater accuracy/precision • greater spatial resolutions • larger areas • new and PV-specific technique development • standards, international oversight
Manufactured Devices	Crystalline Si modules reach 16-19% baselines [M-L] Multicrystalline Si modules: 15-18% baselines [M-L] Polycrystalline thin Si modules: 14-15% baselines [M-L] First polycrystalline thin-film Si modules (pilot): 10% M+ -L] Specialized PV packages for wireless communications and other portable applications [E-L] Polycrystalline (e.g., CIGS) module: 15% validated [M] Amorphous module production: 12% stabilized [E]; 15% stabilized [M-L] Multiple-junction pilot (poly-thin film) demo: 18-20% [L] Concentrator modules: 30% in production [L] Lag time between R&D demonstrations and manufacturing cut by 20% (to 5-8 years) TPV manufacturing with 15-20MW annual capacity [L+] Amorphous, micro-, nanocrystalline MW capacities for architectural, cladding, building integration [M-L] In-line, control, and intelligent diagnostics: Developed and implemented (E-M); start of routine use [M-L] Expanded space product manufacturing (supporting start of recreational/pharmaceutical businesses) [M-L]

Newer Technology and Approaches	
Laboratory Scale	Theoretical predications of optimal materials, structures • novel approaches • user-friendly, transferable algorithms • atom-by-atom structural prediction to specified PV parameters Multiple-junction polycrystalline-based cells validated at >18% [E]; 25% [M-L] Crystalline/non-crystalline cells with efficiencies 20-25% • amorphous/crystalline multijunctions: 20% [E]; >23% [M-L]

	• multijunction poly/amorphous: 20% [M] New materials/processing R&D for PV: • organic semiconductors with efficiencies 7-8% [M] • nanoparticle devices with efficiencies 8-10% [E]; exceeding 15% [M-L] • new classes of conducting transparent oxides for wide use in device technology/improvement [E-L] • improved and environmentally friendly window materials for heteroface cells; development of new p-type semiconductor wide-bandgap semiconductors [E-L] • matrix organic/nanoparticle cell >10% [M]; >15% [L] • nanostructured, optically engineered surfaces for maximum light absorbtion [E-M] Integral encapsulants (direct deposited); diamond-like coatings with durability, low-T process, optical requirements, compatible with thin-film and bulk technologies [M] Research on neural network, multi-sensory robotics, advanced expert systems, & advanced simulation technologies—for research and manufacturing Intense R&D efforts in developing thin-film, polycrystalline cells toward using manufacturing-viable processes • 15% research cells on low-cost substrates, <25 µm thicknesses [E]; 18%, <20µm [M-L] • 20% tandems (with micro- or amorphous Si) [M-L]

Period of Evolution and Expansion 2010-2025	
Improvement in 21st Century Technologies	
Laboratory Scale	Organic semiconductors will reach 10% efficiencies [L-M] New concepts from previous period will become conventional laboratory R&D pursuits, for example: • multijunction, polycrystalline cells with efficiencies 25-28% (research devices) [M] • Organic semiconductor devices in 10% range [E-M] • Nanoparticle/organic and other matrix approaches: 10-12% demonstrations [E-M] • Concetrator cells with 40% efficiency (& beyond)[M] • Optical containment, optical reflectors, etc. are routine inclusions in device processing [M-L]
Manufacturing Environment	New, improved, TCOs introduced into manufacturing, leading to 10% increases in commercial product performance and lower costs [M-L] General product, yield improvements; enhanced production capacities with 25% annual growth in shipments met/exceeded due partially to introduction of new thin-film products/technologies [E-M] Multi-sensory robotics, *knowbotics*, intelligent processing, in-situ diagnostics/controls, statistical processing—coupled with neural networking—mark the entry of PV into 21st century manufacturing Process research leading to manufacturing-line curing of device problems (defects, shorts/shunts, contacts, etc.), guiding toward 100% process line yields Space cell: Emphasis on thin-film technologies (25% AMO) for expanded private sector use (new recreation and biotechno-business).

Newer Technology and Approaches	
	New PV materials: coupling of fabrication systems directly to theoretical optimization guidance and to established *knowbotics*; validation and cataloging of many new PV materials/compounds [E-M] First p-window/n-thin-film heterointerface cells with 10% efficiencies [M-L] Biotechnology: first demonstrations of PV in diagnostic and biomedical devices [M] 3 and 4 junction cells using combinations of nano-, micro- and polycrystalline semiconductors will demonstrate higher efficiency paths to exceeding 30% [L] Nanotechnology: New & enabling PV applications [M-L] • Micromechanical generators with integrated PV • Nano machines, room-temperature superconductor storage, fly wheels, integrated PV • Electronics with integrated PV • Nano-dimension rectifiers/antennae (thermal/cosmic noise)

Period of Establishment, Contribution, and Prosperity 2020-2050 (and beyond)	
Research and Development	
Laboratory and Manufacturing	PV exemplified by huge market penetrations (power generation, new transportation, wireless communications, consumer products, space (consumer, industrial, government) biomedical, integrated electronics, . . .) Addressing next-generations of devices(?) • whole new energy conversion technologies (distant relatives of current PV devices) [M-L+] • "3D PV"—both integrated and random designs using 3-dimensional schemes leading toward 50% efficiencies (and beyond) [L+] • extraordinary performances (demonstrated) [M-L] • PV tuned to new environments ("Aqua-voltaics") New materials, resources, compounds [M- L+] • space exploration: new reserves, new compounds/ elements, naturally occurring pure semiconductors • processing (and manufacturing) in extra-terrestrial environments for earth export, new "domestic" use, and exploration "Old approaches": ultimate performances in marketplace "Rebirth" of now-technology-ready approaches Integration: Biotechnology and Medical Science (probes, (diagnostics, nanosurgery, monitoring, behavioral control); Nanotechnology (electronics, computers, sensors, detectors, etc.)

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13. ABSTRACT *(Maximum 200 words)*
The future investments for photovoltaics *research & development* are contemplated for this new millennium. Current technologies are used as the foundation for what might be expected for the next 50 years. A 'tour' is conducted through what we and our coming generations can anticipate for this technology—emphasizing non-conventional applications beyond the "expected". Next-generation research approaches are predicted indicating the horizon of PV technology. Conjectures of those PV and related technologies that are *beyond* this horizon are presented, with prognosis what our coming generations might have as *their* 'conventional' energy sources.

14. SUBJECT TERMS
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