Energy Research and Development Division
FINAL PROJECT REPORT

# REDUCING THE INSTALLED COST OF CONCENTRATING PHOTOVOLTAICS

Prepared for: California Energy Commission
Prepared by: GreenVolts, Inc.

MARCH 2012
CEC-500-2014-016

GreenVolts™

**PREPARED BY:**

***Primary Author(s):***
J. Scott Shoults
Greg Wagoner

GreenVolts, Inc.
46400 Fremont Blvd.
Fremont, CA 94538

***Contract Number: PIR-07-011***

***Prepared for:***

**California Energy Commission**

Hassan Mohammed
***Contract Manager***

Linda Spiegel
***Office Manager***
***Energy Generation Research Office***

Laurie ten Hope
***Deputy Director***
***ENERGY RESEARCH AND DEVELOPMENT DIVISION***

Robert P. Oglesby
***Executive Director***

**DISCLAIMER**

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

# ACKNOWLEDGEMENTS

Special thanks to members of the PIER team for their ongoing support throughout the development process. In particular, Hassan Mohammed, of the CEC, who championed this program and guided it through the PIER processes.

# PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

*Reducing the Installed Cost of Concentrating Photovoltaics* is the final report for the Reducing the Installed Cost of Concentrating Photovoltaics project (contract number PIR-07-011) conducted by GreenVolts, Inc. The information from this project contributes to Energy Research and Development Division's Renewable Energy Technologies Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

# ABSTRACT

This report summarized the efforts of GreenVolts, Inc. to significantly reduce the installation costs of concentrating photovoltaic systems, the approach taken to identify cost reduction opportunities and the results achieved. Beginning in 2009 GreenVolts set out to develop a new concentrating photovoltaic architecture that would offer the lowest levelized cost of electricity in regions of high direct normal irradiance. GreenVolts set an industry leading installation cost target of $0.10 per watts peak. GreenVolts analyzed every cost driver across the entire concentrating photovoltaic system and ultimately designed a fundamentally new high performance concentrating photovoltaic array that was low-cost to manufacture, install and operate. GreenVolts collected extensive installation cost data for several megawatts peak of their concentrating photovoltaic systems installed at a number of projects throughout California and the southwestern United States. These data verified that GreenVolts achieved major cost reductions in part by using factory pre-assembly to greatly reduce on-site labor costs and by significantly reducing installation material costs via an array design that could be installed on various types of piers and use of array-level inverters to eliminate direct current distribution cables. GreenVolts concluded that the new concentrating photovoltaic solution met the installation cost targets of the project. GreenVolts' solution improved the competitiveness of concentrating photovoltaic, which could lead to the wider adoption of large-scale solar projects. Researchers believed that other concentrating photovoltaic and photovoltaic designers could also significantly reduce their costs by taking a similar approach and applying similar design principles. These cost reductions could provide a range of benefits to California ratepayers and GreenVolts recommended that these opportunities be carefully considered by system vendors and solar project developers.

**Keywords:** GreenVolts, concentrating photovoltaics, CPV, array design, balance of systems, BOS, installation, cost reduction

Please use the following citation for this report:

Shoults, J. Scott; Greg Wagoner. (GreenVolts, Inc.). 2012. ***Reducing the Installed Cost of Concentrating Photovoltaics.*** California Energy Commission. Publication number: CEC-500-2014-016.

# TABLE OF CONTENTS

**Acknowledgements** ..... **i**

**PREFACE** ..... **ii**

**ABSTRACT** ..... **iii**

**TABLE OF CONTENTS** ..... **iv**

**LIST OF FIGURES** ..... **vi**

**LIST OF TABLES** ..... **vii**

**EXECUTIVE SUMMARY** ..... **1**

Introduction ..... 1

Project Purpose ..... 1

Project Results ..... 1

Project Benefits ..... 3

**CHAPTER 1: Introduction** ..... **5**

1.1 Historical Background ..... 5

1.2 Installation Cost and LCOE ..... 6

1.3 Installation Cost Drivers for CPV ..... 6

1.4 Opportunities for Installation Cost Reduction ..... 7

**CHAPTER 2: Project Objectives** ..... **8**

2.1 Installation Cost Target ..... 8

2.2 Lowest Mechanical Installation Cost CPV ..... 8

**CHAPTER 3: Project Approach** ..... **9**

3.1 The Starting Point – Assessment of the CarouSol Design ..... 9

3.1.1 Design Features of the CarouSol ..... 9

3.1.2 Deployment Experience - Deficiencies of the CarouSol ..... 10

3.2 A New Approach ..... 10

3.3 Design for LCOE – A CPV Power Plant Perspective ..... 11

3.4 Design for Performance – An Integrated CPV System Architecture ..... 12

3.5 Design for Low Cost Logistics – From Factory to Project Site ..... 12

3.6 Design for Low Cost Installation – Materials ..... 13
3.7 Design for Low Cost Installation – Labor ..... 13
**CHAPTER 4: Project Outcomes ..... 14**
4.1 An Overview of the GreenVolts Solution ..... 14
4.1.1 GreenVolts CPV Array ..... 14
4.1.2 GreenVolts CPV Modules ..... 15
4.1.3 GreenVolts Factory-Assembled Paddles ..... 15
4.1.4 GreenVolts Two-Axis Tracking Array ..... 17
4.1.5 GreenVolts Integrated System Control Point (SCP) ..... 18
4.1.6 GreenVolts ISIS™ (Intelligent Solar Information System) ..... 18
4.1.7 GreenVolts Reference 64–Array CPV Power Block ..... 19
4.1.8 Scope of the GreenVolts CEC PIER Installation Cost Reduction Study ..... 19
4.2 Features of the GreenVolts Array That Reduce CPV Installation Costs ..... 20
4.3 GreenVolts CPV Array Installation Process ..... 20
4.3.1 GreenVolts CPV Array Installation Step 1: AC Distribution Cables ..... 21
4.3.2 GreenVolts CPV Array Installation Step 2: Drilling and Pouring Piers ..... 22
4.3.3 GreenVolts CPV Array Installation Step 3: Setting and Aligning Stanchions ..... 23
4.3.4 GreenVolts CPV Array Installation Step 4: Assembling Roll Beam Sections ..... 25
4.3.5 GreenVolts CPV Array Installation Step 5: Installing Roll Beam Sections ..... 26
4.3.6 GreenVolts CPV Array Installation Step 6: Installing Factory-Assembled Paddles 27
4.3.7 GreenVolts CPV Array Installation Step 7: Hanging and Connecting the SCP ..... 30
4.3.8 Completed GreenVolts CPV Arrays ..... 31
4.4 GreenVolts Detailed Installation Cost Study ..... 32
4.5 GreenVolts CPV Installation Cost Breakdowns ..... 32
4.6 Comparison between GreenVolts CPV and PV Installation Costs ..... 34
4.7 GreenVolts Speed of Installation Data ..... 34
**CHAPTER 5: Conclusion ..... 36**
5.1 Installation Materials Cost Reduction Opportunities ..... 36

5.1.1 Distributed Array-Level Inverters ..... 36
5.1.2 Distributed Modular Array Architecture ..... 36
5.1.3 Wireless Communications ..... 36
5.2 Installation Labor Cost Reduction Opportunities ..... 36
5.2.1 Factory Pre-Assembly ..... 36
5.2.2 Design for Shipping and Site Logistics ..... 36
5.2.3 Distributed Modular Array Architecture ..... 36
5.3 Broad Applicability to Other CPV and PV System Architectures ..... 36
**CHAPTER 6: Recommendations ..... 37**
**CHAPTER 7: Public Benefits to California ..... 38**
**REFERENCES ..... 39**
**GLOSSARY ..... 40**
**APPENDIX A: The Levelized Cost of Electricity (LCOE) ..... 1**
**APPENDIX B: Direct Normal Irradiance Map of California ..... 1**
**APPENDIX C: GreenVolts Reference CPV Power Block – 1.229 MWp ..... 1**
**APPENDIX D: Example GreenVolts CPV Installations ..... 1**
**APPENDIX E: GreenVolts CPV Dual Use Installations ..... 1**
**APPENDIX F: GreenVolts Solutions for Low Cost Logistics ..... 1**
**APPENDIX G: GreenVolts Detailed Installation Cost Data ..... 1**
**APPENDIX H: Comparison between GreenVolts CPV and PV Installation Costs ..... 1**
**APPENDIX I: Additional GreenVolts Installations ..... 1**

## LIST OF FIGURES

Figure 1: Fixed Mount PV BOS Cost Reduction Roadmap from GTM Research [1] ..... 6
Figure 2: GreenVolts Former CarouSol CPV Arrays ..... 9
Figure 3: GreenVolts CPV Array ..... 14
Figure 4: GreenVolts High Performance CPV Module ..... 15
Figure 5: GreenVolts Paddle Frame ..... 16
Figure 6: GreenVolts CPV Paddle Pair ..... 16
Figure 7: GreenVolts Two-Axis Tracking Array with Installed Paddle Pairs ..... 17

Figure 8: GreenVolts Support Stanchion Mounted to Supporting Pier and A Roll Beam Assembly with Tilt Axle ..... 17
Figure 9: GreenVolts System Control Point (SCP) ..... 18
Figure 10: GreenVolts ISIS™ (Intelligent Solar Information System) ..... 18
Figure 11: AC Wiring Configuration between GreenVolts Scps and the MV XFMRS ..... 21
Figure 12: Drilling and Pouring Piers (5 per CPV array) ..... 22
Figure 13: Setting and Aligning Mounting Stanchions (5 per CPV array) ..... 23
Figure 14: Installed CPV Array Support Stanchions on Piers (Shown for Two Arrays) ..... 24
Figure 15: Assembling a Roll Beam and Tilt Axle (4 per CPV Array) ..... 25
Figure 16: Hoisting and Installing a Roll Beam/Tilt Axle Assembly (4 per CPV Array) ..... 26
Figure 17: Installing a Factory-Assembled CPV Paddle (8 per CPV Array) ..... 27
Figure 18: Installing a Factory-Assembled CPV Paddle – Another View ..... 28
Figure 19: GreenVolts Paddle Lifting Bar (Yellow) – Paddle Vertically on Pallet ..... 29
Figure 20: GreenVolts Paddle Lifting Bar (Yellow) – Paddle Horizontal For Installation ..... 29
Figure 21: GreenVolts Paddle Pair, Curve Bars and Attachment Truss ..... 30
Figure 22: Hanging and Connecting the System Control Point (SCP) ..... 30
Figure 23: Completed GreenVolts CPV Arrays – the Nearest Array Shows SCP and 480 VAC Disconnect ..... 31
Figure 24a: GreenVolts Installation Cost Breakdowns ..... 32
Figure 24b: GreenVolts Installation Cost Breakdowns ..... 33
Figure 24c: GreenVolts Installation Cost Breakdowns ..... 33
Figure 25: Comparison between GreenVolts CPV and PV Installation Costs ..... 34

## LIST OF TABLES

Table 1: GreenVolts Design Features that Enable Significantly Reduced CPV Installation Costs 20
Table 2: Example AC Cable Lengths for a Standard GreenVolts 64-Array CPV Power Block ..... 21
Table 3: Example Installation Unit Savings through Use of Shared Stanchions ..... 24
Table 4: Summary of the Project Scope in GreenVolts Installation Cost Study for the CEC PIER Project ..... 32
Table 5: Speed of Installation of GreenVolts CPV Array Elements and Associated Labor Costs 35

# EXECUTIVE SUMMARY

## Introduction

Reducing the overall cost of renewable energy systems and improving the lifetime return on investment (ROI) from their installation and long-term operation will enable the continued deployment of renewable energy technologies in California, which is crucial to meeting the state's 33 percent Renewable Portfolio Standard (RPS) mandate.

Solar photovoltaics (PV) are a major component of the renewable energy technology portfolio, in addition to wind generation and other technologies. California has excellent solar resources and is a prime region for the large-scale deployment of a wide variety of PV technologies across a range of major market segments throughout the state. The potent solar resource in California enables PV generating systems to produce a high level of electrical energy. This high productivity is an essential driver for both an attractive rate of return to solar project investors and the potential to reduce the cost of electricity to California ratepayers.

Improving the performance of solar technologies through the improved conversion of solar energy into electricity and reducing the costs associated with procuring and installing PV equipment and operating and maintaining PV generating facilities over a typical 20-year operating lifetime are key measures for successful deployment of PV technology in California. By maximizing energy production and minimizing costs it is possible to significantly reduce the relative cost and improve the rate of return. This will further attract investors in solar projects and still provide a positive return under lower electricity rates paid to the owners of solar generating facilities.

## Project Purpose

GreenVolts was engaged in an overall development effort to design, manufacture and demonstrate a fully-integrated concentrating photovoltaic (CPV) system solution that would offer the lowest levelized cost of electricity (LCOE) in regions of high direct normal irradiance (DNI). DNI refers to the intensity of sunlight usable by CPV.

The objective of this project was to reduce the installation portion of CPV costs. The installation cost target was set at $0.10 per watts peak (Wp), which would be significantly lower than existing PV technologies. A broader goal of this project was to achieve the lowest mechanical installation cost of any CPV technology. CPV mechanical installation costs have typically been higher than other PV technologies.

## Project Results

Researchers developed an innovative high-efficiency CPV solution that achieved a significantly higher level of performance when compared to traditional flat-plate PV and that also was designed to have a significantly lower cost to procure, install and operate. These advantages combined to provide a low LCOE that could help contribute to the growth of solar energy throughout California.

This report describes the aspects of the development effort, including:

- Material and labor drivers of installation costs.
- Relevant design elements of both the GreenVolts system and power plants built with GreenVolts systems.
- Site preparation, construction and installation procedures.
- The demonstrated measurable advantages of the GreenVolts system as compared to traditional PV solutions.

GreenVolts successfully developed a new, fully integrated, CPV system architecture and has deployed it in plants throughout California and the Southwestern United States. These successes have allowed GreenVolts to not only demonstrate the performance advantages of the new system but also to quantify the installation costs at scale.

The first outcome of the project was the firm conclusion that a self-ballasted non-ground penetrating design would not meet the performance, cost and reliability requirements for the large-scale CPV market. A detailed engineering analysis showed that although anchoring structures would be required, they could be intelligently designed so that even though they would require additional material the overall system would achieve competitive cost targets. GreenVolts achieved a $0.09/Wp installation labor cost, which was far below that of traditional PV systems. GreenVolts' overall installation costs including balance of systems (BOS) materials such as copper cabling were also significantly lower than that of traditional PV systems. These materials cost advantages were achieved in part because GreenVolts' new design uses less wire per MWp of generating capacity.

The total installation costs were projected to continue falling considerably as the performance of CPV systems continued to rise and further economies of scale were achieved. The efficiency of the high performance multi-junction solar cells used in GreenVolts' CPV systems have been steadily improving by approximately one percent per year for the last 10 years and expectations were for that level of improvement to continue. This directly reduced the relative costs per MWp of generating capacity for new CPV installations year by year.

A secondary outcome of this project was that the new GreenVolts array design allowed for dual-use of the land for a CPV installation; for example, agricultural crops, livestock or parking lots. Researchers believed that this could open up the possibility of deployments on agricultural lands, with both operational benefits and real estate savings.

The principle conclusion from this project was that the significantly reduced CPV installation costs that were projected were not only feasible but were in fact achieved. These reduced installation costs applied to moderately sized projects and further reductions were expected for plants larger than 10 megawatts (MW). GreenVolts developed and implemented a system design that reduced both the labor and the materials needed to install and interconnect a CPV array field by:

- Constructing a modular system architecture using shared support structures.
- Minimizing the number of ground foundation piers and mounting supports.

- Utilizing pre-fabricated factory assemblies and integrated power electronics sub-systems with on-board performance monitoring and wireless communications.
- Employing distributed inverters, which eliminated both the engineering and materials associated with a large direct current (DC) infrastructure.

Researchers recommended that new CPV systems be developed that leverage the fundamental concepts defined in this project. Other CPV and PV system designers should consider incorporating the innovative concepts developed during this project to bring the advantages of cost reduction to a wider range of markets. This in turn will further reduce the installation cost of solar power generation and attract new investors to develop and deploy new solar power plants at commercial, industrial and utility scale. Additional innovations and refinements could help to further lower the installation and equipment costs of CPV systems.

## Project Benefits

This project benefitted California by demonstrating that CPV systems could be installed quickly without heavy equipment, that the land used for CPV installations could potentially be available for other uses such as agriculture, and that a higher ROI could be realized for CPV project investors. Increased adoption of CPV projects could help California meet its overall Renewables Portfolio Standard goals and could potentially reduce electricity rates for California rate payers.

# CHAPTER 1: Introduction

## 1.1 Historical Background

GreenVolts, Inc., founded in 2005 and currently located in Fremont, CA, was design and manufactures low cost, high performance concentrating photovoltaic (CPV) systems. The company has designed, tested and deployed a series of technologies and architectures in an effort to develop the most competitive CPV solutions available.

In early 2009, GreenVolts developed its first generation CPV technology, known then as the "CarouSol", which featured an ultra-low profile, non-ground penetrating design. However, in trying to bring this system to market they discovered deficiencies in design, basic architecture and its manufacturability that prevented this approach from being cost-effective. Based on this experience and the educationall events gained, GreenVolts seized the opportunity to conduct a comprehensive design assessment to understand the root causes of the problems encountered.

Incorporating all of the firsthand knowledge obtained in manufacturing, system deployment, reliability testing and field operations, GreenVolts identified the key aspects of both component design and system architecture that would need to be addressed in a fundamentally different way. It also established new cost and performance targets that would need to be met to achieve an industry leading CPV solution. With these objectives and a revitalized corporate mandate, the GreenVolts team went back to the drawing board to develop a completely new system architecture from the ground up.

To ensure the new solution would be the most competitive available, it was necessary to look at not only the CPV array itself, but consider the entire CPV power plant as a whole. It was also necessary to evaluate both performance and cost over the entire project lifetime, from planning, to installation and commissioning, daily operation and monitoring, and long term servicing and maintenance. Thus, the principle drivers of the redesign effort were to achieve: high performance, low equipment cost, rapid low-cost installation, reliability, and serviceability.

The core of the entire redesign effort was extensive engineering analysis, complex modeling and simulation, rigorous lab testing, and long-term field testing. Everything about the design and operation was considered and rolled up into a comprehensive system model. At the plant level, a long term performance and operations model was developed.

As part of its overall performance improvement and cost reduction efforts, GreenVolts applied to the CEC PIER Program for a grant to study installation costs of CPV technologies and develop a new solution that would dramatically reduce what had been at that time one of the major barriers to the competitiveness of CPV systems, installation costs.

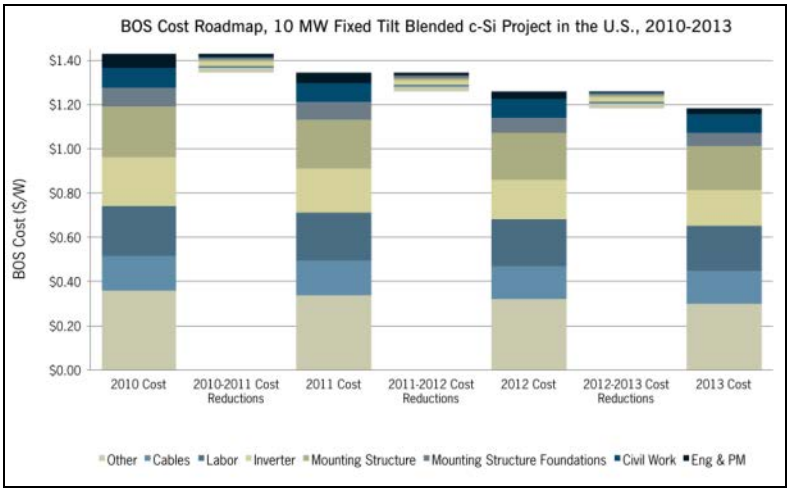
Employing a model for the overall Levelized Cost of Electricity (LCOE, see Appendix I for details) for the complete solution, GreenVolts set aggressive targets for the installation cost of its

CPV system and integrated these into the overall system cost and LCOE models, which were the ultimate basis for assessing the results of the redesign efforts.

## 1.2 Installation Cost and LCOE

As shown in Appendix I, installation costs are a principle element of the LCOE of a CPV, PV or other renewable energy power plant. Installation costs are a subset of what are called Balance of Systems (BOS) costs. With the rapidly falling prices for PV modules, and the ongoing consistent performance improvement of CPV modules, there is a strong market pressure to drive BOS cost reductions, and development efforts in this area are a focus of the PV and CPV industry.

**Figure 1: Fixed Mount PV BOS Cost Reduction Roadmap from GTM Research [1]**




## 1.3 Installation Cost Drivers for CPV

Examining the figure above, and excluding the inverter equipment cost component, the remaining cost components relating to construction and installation represent approximately 75 percent of the total BOS cost budget. Specifically, the principle drivers of installation cost are

- Site preparation, such as civil work, including trenching ($/site)
- Structural foundations and mounting structure materials ($/unit)
- Cables, including conduits and electrical BOS equipment ($/unit)
- Installation Labor ($/hr)

For CPV systems these costs were even higher than those of PV, and represented a barrier to their overall competitiveness and widespread adoption. GreenVolts recognized this as a major opportunity to develop innovative solutions that would significantly reduce these costs. Key to their success, GreenVolts took a holistic systems approach. In this way, they had additional design control and could realize additional, synergistic benefits that would not be possible by considering first one component, then another in separate efforts.

## 1.4 Opportunities for Installation Cost Reduction

To reduce installation costs for CPV, the GreenVolts design strategy focused on reducing the:

- Number of foundations and mounting structures needed – (reduce units/MWp)
- Lengths and types of cables used – (reduce $/ft)
- Hours and skill levels of installation labor– (reduce hrs/MWp and $/hr)

# CHAPTER 2:
# Project Objectives

The total installation costs of CPV (and PV) systems can be aggregated into two general categories:

- Installation materials costs (mechanical and electrical)
- Installation labor costs (mechanical and electrical)

Materials and labor costs are subdivided into mechanical and electrical sub-categories because (1) they generally represent different elements of the overall system design, and therefore are amenable to different design features (and areas of design expertise); and (2) both the unit costs and hourly costs are considerably different for each sub-category.

As can be seen in Figure 1, in 2010 installation labor for fixed mount PV systems was >$0.20/Wp. As has been shown in other studies,[2,3] this cost was significantly higher for one-axis tracking PV systems, and as might be expected were even higher for two-axis tracking CPV systems due to their requirement for high degrees of accuracy.

## 2.1 Installation Cost Target

As a major component of the overall installation cost of CPV systems, GreenVolts not only recognized labor as a significant opportunity to reduce overall costs, it also aligned well with the principle objective of the GreenVolts CEC PIER project.

Specifically, GreenVolts established the aggressive target of reducing the installation labor cost for its CPV systems to no more than $0.10/Wp. To give a sense of how aggressive this target was, it represented a cost level that would be about half of that of fixed mount PV systems, and far less than half of that for one-axis tracking PV systems.

To achieve this target, it would be necessary for the GreenVolts team to consider every aspect of system architecture, structural and component materials, assembly logistics, installation logistics and BOS design.

## 2.2 Lowest Mechanical Installation Cost CPV

In addition to the specific installation cost target, a broader goal of the GreenVolts PIER project was to achieve the lowest mechanical installation cost of any CPV technology. This required GreenVolts to undertake a detailed analysis of all its installations costs, identify the leading cost drivers and opportunities to reduce them, and develop new solutions to achieve the goals that had been set.

Considering how aggressive these goals were, they strongly suggested that a completely new CPV architecture needed to be developed, but if it could be achieved it would establish a new competitive benchmark for CPV. In the end, that is exactly what the GreenVolts team did, and it is what ultimately enabled them to achieve the objectives that they had set.

# CHAPTER 3:
# Project Approach

## 3.1 The Starting Point – Assessment of the CarouSol Design

**Figure 2: GreenVolts Former CarouSol CPV Arrays**

From 2005 through 2008, GreenVolts developed its initial CPV array architecture, known as the CarouSol. Several CarouSols arranged in a small hexagonal pattern are shown in the figure above.

The name for the system derived from the configuration and actuation of the two-axis tracking geometry of each array. Being low to the ground (about 1.5 m) and relatively small (about 6.5 m in diameter), each array would independently rotate in a horizontal plane parallel to the ground (like a carousel), and each row of concentrating reflectors would tilt to point the mirrors at the sun and direct the focused beam of sunlight on to a small (1 $cm^2$) high efficiency solar cell sitting in front of it.

At the time, it represented a new concept in CPV design with the goal that the installation would be rapid, low cost and minimally disruptive to the project site.

### 3.1.1 Design Features of the CarouSol

The CarouSol contained many innovative design features, which at least on paper, seemed promising:

- 176 semi-independent concentrating reflectors (mirrors) and CPV Power Units (~3 kWp)
- Ultra-low-to-ground profile
- Non-penetrating ground surface mounting – no foundations, only ground ties or ballasts
- Face-down stow of CPV modules during nighttime or bad weather conditions

### 3.1.2 Deployment Experience - Deficiencies of the CarouSol

As a result of the learning from manufacturing, and installing and testing many CarouSols, a difficult list of fundamental and systemic problems were identified in the design, including:

- The 6.5 m diameter circular design meant that CarouSols could not be pre-assembled and transported on flatbed trucks or in shipping containers
- The many individual parts and differently sized and shaped pieces for each CarouSol represented a significant manufacturing and logistics challenge
- The aluminum based design, although lower in weight than steel, meant that many standard fabrication and assembly processes could not be used
- The lightweight material was not conducive to long (20+ years) life, and mechanical wear and stress was obvious in very short periods of time. The on-site assembly of many dozens of parts per array, which was necessary because of its complex, circular design, was extremely expensive, slow, and highly error prone
- Being both mirror-based and close to the ground made soiling a significant problem
- Wiring between individual CPV power units was difficult to manage and prone to damage
- The concentrating mirrors had the ability to focus concentrated (650X) sunlight outside of the receivers which represented a significant safety hazard
- Because the arrays were not hard mounted to foundations, their placement was inaccurate and not always stable –and accurate alignment is critical for CPV tracking
- At ~3 kWp per CarouSol, each 1 MWp Power Block required hundreds of independent connections to the underground DC distribution lines that fed into the central inverters

## 3.2 A New Approach

Careful evaluation of all of the educational events from the experience with the CarouSol, and in particular the root causes of the specific and systemic deficiencies of the design, led the GreenVolts team to identify key guiding principles that needed to be implemented in the new system architecture. These included:

- Switching from mirror based concentrating optics to lens based
    - This reduces soiling impact, improves reliability, safety and performance
- Switching from aluminum to steel enclosures and structural supports
    - This significantly reduces materials costs and supported longevity
- Elevating the arrays to a modest height off the ground
    - This reduces soiling and enables dual use of the land
- Significantly increase the power per array
    - This reduces the amount of distribution lines and connections in the array field

- Transitioning from central inverters to distributed array-level inverters
    - For CPV, this reduces cost and provides other benefits since each two-axis tracking array already requires tracker control electronics, performance monitoring systems and field communications
    - It also provides the advantage of requiring only AC distribution cables at the site.
- Transitioning from wired to wireless field communications
- Designing the components so that they can be manufactured using existing high volume, low cost manufacturing techniques
    - These included semiconductor assembly, metal stamping and roll forming, and robotic assembly
- Making maximum advantage of component integration (reduce parts count) and factory pre-assembly
    - This greatly reduces the amount of assembly that occurs in the field, which both reduces labor and improves quality
- Designing the components and factory assemblies so that they can easily and efficiently be loaded and unloaded into shipping containers
- Using common mechanical fasteners and electrical interconnects throughout
- Designing a system that had an appealing architectural appearance

With these principles, educational events from the past and others in mind, new engineering design, simulation and testing capabilities, and a detail competitive cost model, GreenVolts set out on the development of its 2nd generation CPV system design.

## 3.3 Design for LCOE – A CPV Power Plant Perspective

All large-scale CPV (and PV) power plants consist of a hierarchy of interconnected assemblies:

- Individual modules are strung together electrically in series to achieve the desired operating voltage (typically 600 or 1000 VDC in the US)
- Strings are grouped together into sub-arrays that are mounted on to the same rack/tracker (or portion thereof) and connected together electrically in parallel
- Sub-arrays may be further connected together electrically in parallel to form arrays
- Distribution lines then run from the array(s) to one or more central collection points

Further (beyond the scope of this report, but provided for reference):

- The AC output of multiple arrays may then be further combined together before entering a medium voltage (MVAC) transformer (XMFR) and other MVAC BOS equipment before interconnecting with the grid

- There are also several essential Balance-of-Plant (BOP) subsystems including metering, monitoring, metrology station(s), security systems, and plant communications (typically the internet), and others.

It was from this overall perspective of the power plant, its full installation and long-term operations that GreenVolts designed its new CPV array to minimize LCOE.

## 3.4 Design for Performance – An Integrated CPV System Architecture

High concentrating (HCPV) arrays, such as those developed by GreenVolts (>1000X) are different than standard (non-concentrating) PV arrays in that they *require* precision two-axis tracking of the sun to ensure the highly focused beam of sunlight falls directly on the very small (≤ 1 cm2) high efficiency solar cell. Each tracker therefore provides a natural "building block" upon which to layout and deploy CPV power plants.

Moreover, because each tracker requires its own power supply and control electronics, it further provides a convenient architectural point to integrate additional functions including: an array-level inverter, performance monitoring sensors, feedback control systems, autonomous computer control, local data storage, and field communications equipment. By integrating all of these systems into a single enclosure mounted on to each array, it is possible to achieve both improved performance and significant cost savings.

Similarly, by regarding the entire CPV array as an integrated system, and evaluating all of the optical, mechanical and electrical subsystems together, it is possible to develop an overall array architecture that minimizes and standardizes the use of materials and key components such as motors and actuators by sharing them across a distributed modular configuration.

This is precisely the approach that was taken in the redesign of its CPV array, and as will be discussed in the next chapter, the principle of integrated modularity was implemented throughout the design.

## 3.5 Design for Low Cost Logistics – From Factory to Project Site

Taking the principle of integrated modularity even further, in addition to functional design, it is also possible to take into consideration the *logistical* aspects of the manufacturing, shipping, installation and long term maintenance of the arrays. These operational costs span the entire lifecycle of a power plant, from the factory, to its installation, and throughout its lifetime.

Once various system components are designed for integration, the components can be pre-assembled in the factory, improving quality and lowering cost. The assemblies are designed together such that transportation to the project site is less costly and organized in such a way as to facilitate rapid, low cost installation once they are received.

That is, the pre-fabricated components and pre-assembled units should easily load into the containers, and be easily unloaded at the project site, with a minimum amount of loading equipment and a minimum amount of shipping materials. This approach has proven to both

dramatically lower shipping costs and significantly lower installation costs while minimizing the amount of packaging materials that need to be discarded/recycled.

## 3.6 Design for Low Cost Installation – Materials

Having established this context; now to discuss the specific focus of the GreenVolts CEC PIER project, and the goal to significantly reduce the installation cost of CPV. As has been discussed, these costs are driven by the design of the array, the installation processes that must be performed on site, and the design of the distribution network that runs throughout the site.

In this report, solutions for reducing four major CPV installation materials costs are discussed:

- The power distribution network of the site which delivers electrical power from the arrays to a common collection point prior to interconnection with the grid
- The structural foundations
- The support structures for the arrays
- The assembly and interconnection of the two-axis tracking CPV arrays

## 3.7 Design for Low Cost Installation – Labor

Smart design choices allow for a significant reduction in the amount of material providing savings in total materials cost, and enabling significant savings in labor costs. The integrated modular array architecture and the use of factory pre-assembled subsystems have resulted in dramatic labor cost reductions during both transportation and installation.

Additionally, the design also greatly reduces CPV installation labor costs for:

- Trenching and laying the distribution cables
- Drilling and pouring the foundations
- Erecting the support structures
- Assembling and interconnecting the CPV arrays

# CHAPTER 4:
# Project Outcomes

## 4.1 An Overview of the GreenVolts Solution

From 2009 through 2011, GreenVolts developed, tested and refined the design of its next generation CPV array solution. Based on the educational events and principles discussed in the previous section, the new architecture, shown in the figure below, represented a complete departure from the prior design. Rather than sitting directly on the ground, which directly resulted in numerous problems, the new design is an elevated array that offers many advantages; and as will be discussed below, the most relevant of which to this study are the dramatically lower installation costs, which set a new competitive threshold in the industry.

### 4.1.1 GreenVolts CPV Array

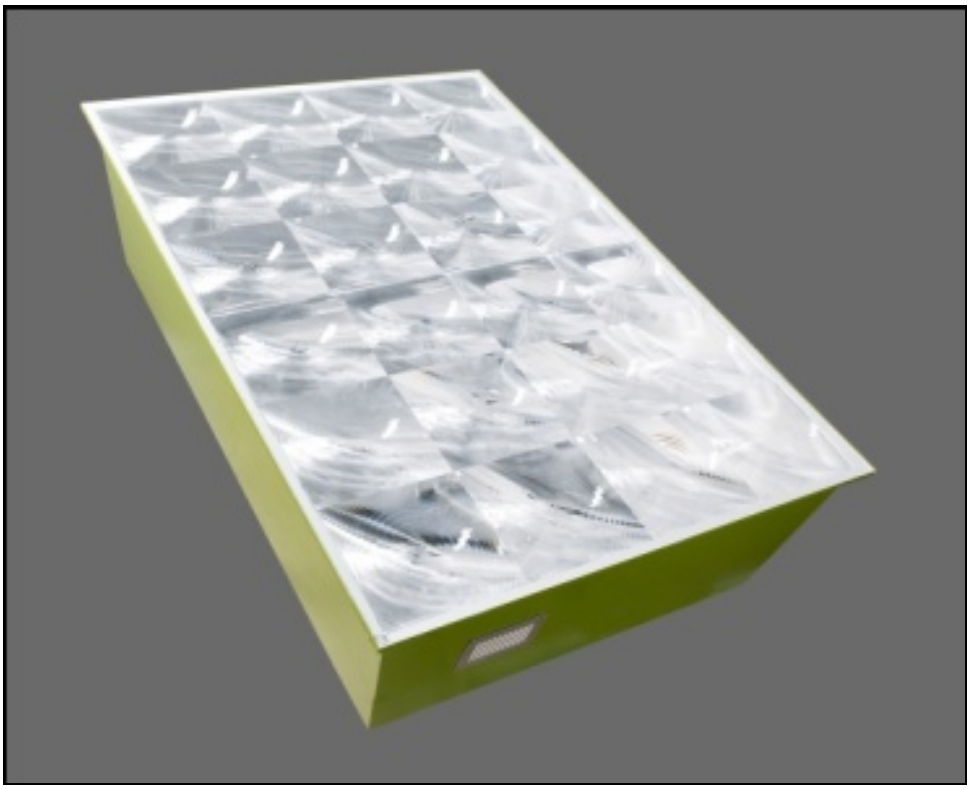
**Figure 3: GreenVolts CPV Array**

The GreenVolts CPV array consists of the following principle elements:

- Five supporting stanchions (two of which may be shared between adjoining arrays)
- Four horizontal roll beam segments, roll bearings and a central roll motor
- A tilt axle on each roll beam segment, that supports
- Two paddle assemblies (8 paddles per array), each of which holds
- Eight CPV modules (64 modules per array)
- And a mounted system control point (electronics)

### 4.1.2 GreenVolts CPV Modules

**Figure 4: GreenVolts High Performance CPV Module**



The optical component of the GreenVolts CPV array is the high performance CPV module. The glass face, which covers about one square meter, contains 24 Fresnel lenses are arranged in a continuous parquet, where each lens focuses sunlight at approximately 1300X. Below each of the lenses is a CPV power unit (24 in total) that incorporates a high performance receiver based on a high efficiency (~39 percent) multi-junction solar cell.

Because the new GreenVolts CPV module uses Fresnel lenses rather than mirrors, it is much more reliable under long term environmental and operating stresses, and it suffers far less of an impact from soiling. The modules also incorporate advanced secondary optics and both thermal management and pressure equilibration features.

In the rare event that a module needs to be replaced, it is an independent Field Replaceable Unit (FRU) changeable by removing 3 fasteners, 2 wire connectors and a grounding strap.

### 4.1.3 GreenVolts Factory-Assembled Paddles

Each GreenVolts paddle is made from welded steel and supports eight CPV modules, which are assembled, aligned, interconnected and fully tested in the factory. The paddles are delivered as field installable units, and require a minimum of installation time to fasten and connect.

**Figure 5: GreenVolts Paddle Frame**

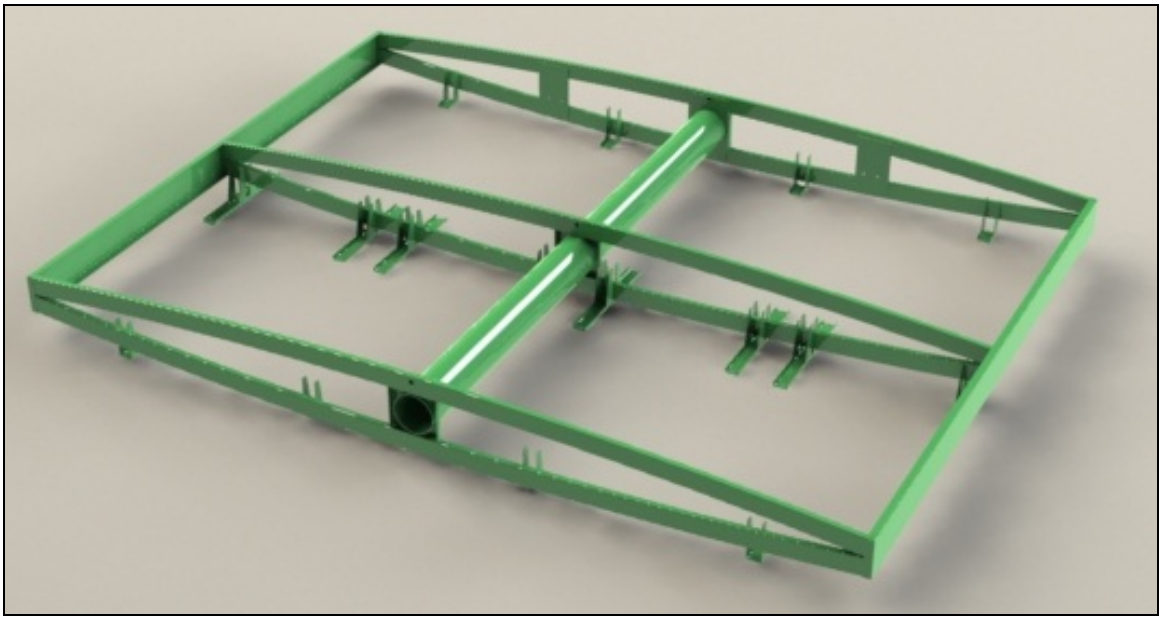
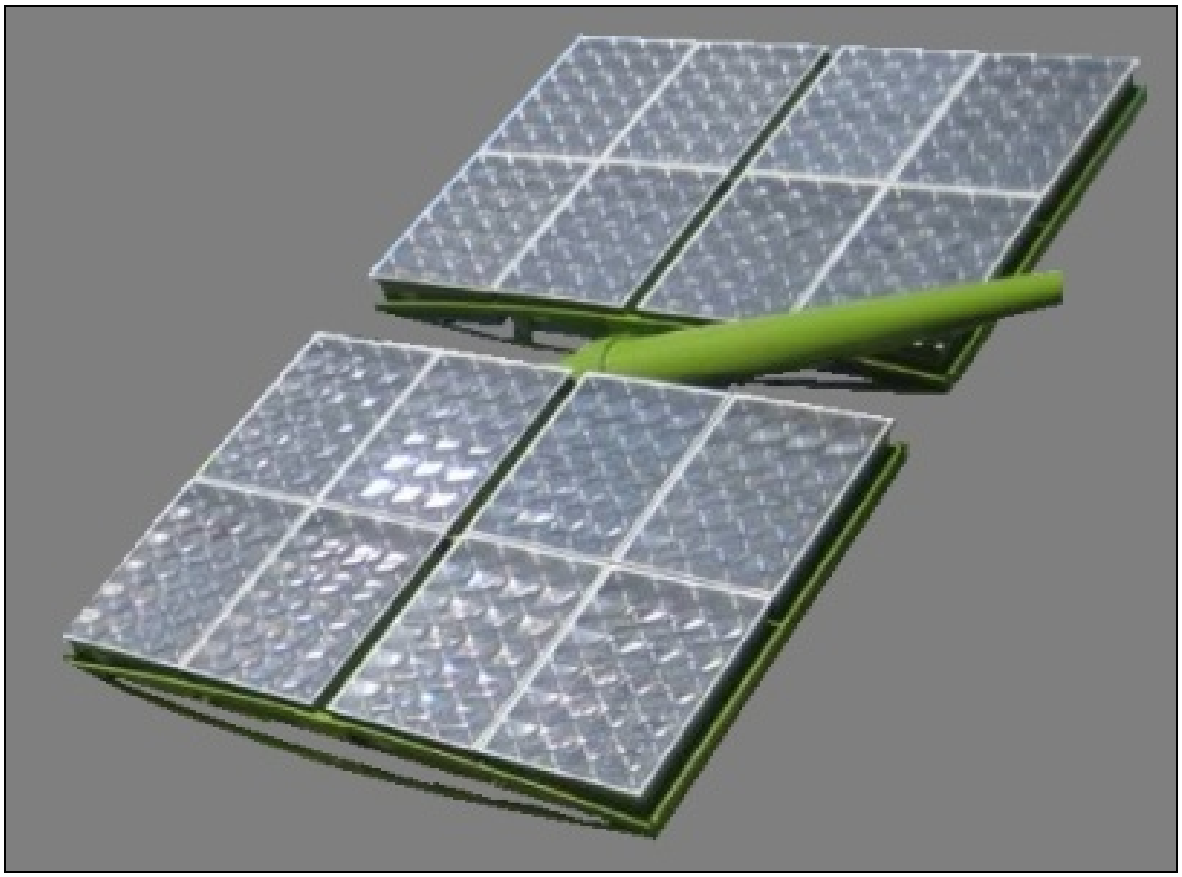
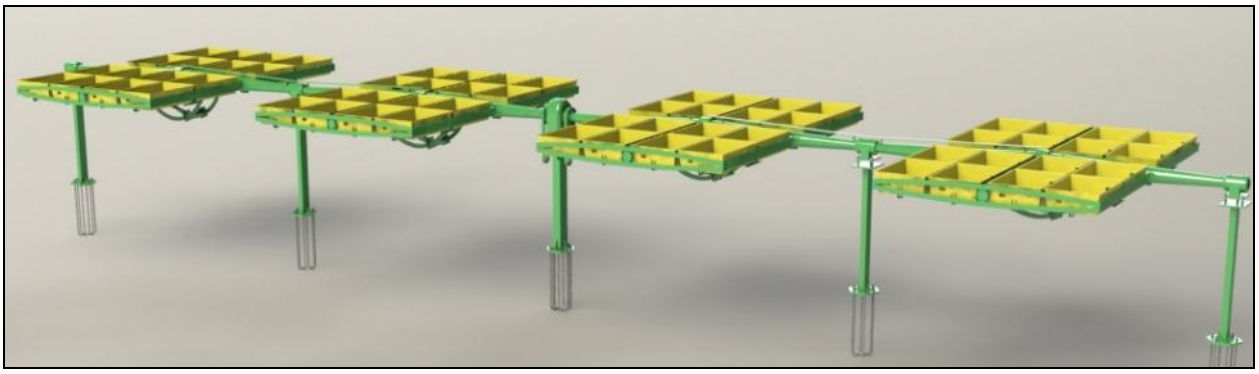


**Figure 6: GreenVolts CPV Paddle Pair**



### 4.1.4 GreenVolts Two-Axis Tracking Array

**Figure 7: GreenVolts Two-Axis Tracking Array with Installed Paddle Pairs**



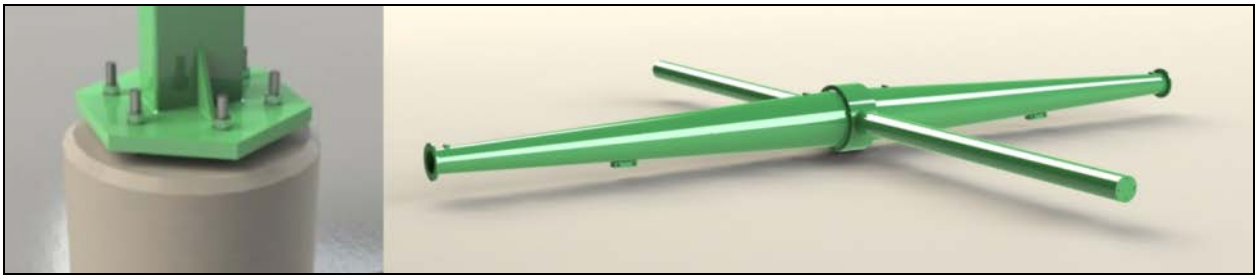
An assembled GreenVolts two-axis tracking array is shown in the figure above. The horizontal roll beam, which sits atop the supporting stanchions, is installed at the project site.

Roll actuation allows the paddles to rotate to any position from the East horizon to the West horizon. In addition, a unique feature of the design, the paddles will roll to point the modules face down at night or during periods of bad weather to protect them and keep them clean.

Tilt actuation allow the paddles to point directly at the sun during seasonal variation, and is controlled by a linear actuator that is attached to each paddle pair.

The figure below shows a stanchion mounted to its supporting pier and a single roll beam segment with its tilt axle.

**Figure 8: GreenVolts Support Stanchion Mounted to Supporting Pier and A Roll Beam Assembly with Tilt Axle**



### 4.1.5 GreenVolts Integrated System Control Point (SCP)

**Figure 9: GreenVolts System Control Point (SCP)**

The GreenVolts SCP integrates a wide range of power and control functionalities, including:

- Two independent MPPT high efficiency inverters
- Tracker motion control, actuation feedback and power supplies
- On-board GPS and Wi-Fi
- High performance CPU and Linux based Operating System
- High capacity non-volatile memory

### 4.1.6 GreenVolts ISIS™ (Intelligent Solar Information System)

**Figure 10: GreenVolts ISIS™ (Intelligent Solar Information System)**

GreenVolts ISIS provides detailed system monitoring, alerting and performance analytics.

### 4.1.7 GreenVolts Reference 64–Array CPV Power Block

The figure in Appendix III shows the schematic layout of a reference GreenVolts CPV power block with

- 64 GreenVolts CPV arrays, arranged in to 16 shared-stanchion four-array groups
- 480 VAC, 3-phase power distribution lines
- Central MVAC transformer (on pad) and distribution line

In the next section, the significant material cost advantages that are obtained as a result of running only AC power distribution cables under the array field are discussed in detail.

### 4.1.8 Scope of the GreenVolts CEC PIER Installation Cost Reduction Study

To focus on the installation costs of CPV power plants that specifically apply to GreenVolts CPV Arrays, the scope of the installation cost reductions reported in this CEC PIER study includes:

- 480 VAC, 3 phase power distribution network
- Piers (5 or less per CPV array)
- Stanchions and tracker (5 or less per CPV array)
- CPV paddle assemblies (8 per CPV array)
- System control point (SCP, 1 per CPV array)

but does not include:

- The equipment costs of the Modules and Inverters
- The equipment and labor costs of the medium voltage transformer and all medium voltage BOS equipment
- The equipment and labor costs of the Balance of Plant equipment and infrastructure

## 4.2 Features of the GreenVolts Array That Reduce CPV Installation Costs

**Table 1: GreenVolts Design Features that Enable Significantly Reduced CPV Installation Costs**

| System Element | CPV Installation Cost Reducing Design Features |
|---|---|
| Power Distribution Lines | • All 480 VAC, 3 phase (no DC distribution lines)<br>– Significantly lower cost per MWp |
| Foundations | • Far smaller piers per array than other CPV<br>• Far fewer piers per MWp than PV<br>– Both drive significantly less materials and labor |
| Tracker | • Modular segments – no heavy equipment, minimal site labor<br>• Shared stanchions – reduced materials and labor |
| CPV Modules | • Factory assembled, pre-wired Paddles – minimal site labor<br>• High performance modules – increases Wp/array |
| Inverter & Electronics | • Integrated system control point – no pads, minimal site labor<br>• Serially connect multiple inverters before "home run" to AC distribution switch – lowers wire costs |

## 4.3 GreenVolts CPV Array Installation Process

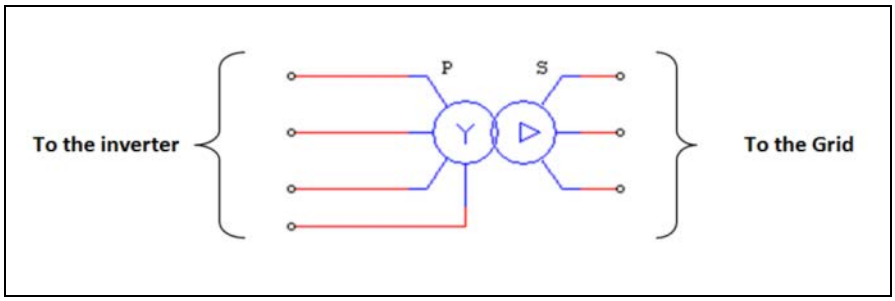
The low cost installation of GreenVolts CPV arrays consists of seven principle steps:

1. Trenching and laying AC distribution cables
2. Constructing piers
3. Setting and aligning stanchions
4. Assembling roll beam sections
5. Hoisting and installing roll beam sections
6. Installing factory-assembled paddles
7. Hanging and connecting the SCP

The sections below describe each of these installation process steps.

### 4.3.1 GreenVolts CPV Array Installation Step 1: AC Distribution Cables

**Figure 11: AC Wiring Configuration between GreenVolts Scps and the MV XFMRS**




Each GreenVolts CPV array connects to the AC field distribution network via its system control point (SCP) through an AC disconnect.

The output of a SCP is three phase, 480 VAC wired in a neutral-Y configuration, and the maximum sustained output current is hardware limited to 20 Amps AC.

An important cost savings feature of the GreenVolts SCP is that up to four units can be connected in a series. This matches the four arrays that may be interconnected mechanically in array groups via shared stanchions.

As shown in Appendix III, a 64-array GreenVolts CPV power block may be configured into 16 4-array groups, each having its own AC home run to the central MVAC XMFR. This allows for a significant reduction in trenching, cabling, conduit and associated labor.

The table below summaries the approximate cable lengths by group location in the field, assuming a standard layout and a 12 meter east-west spacing between columns of array groups.

**Table 2: Example AC Cable Lengths for a Standard GreenVolts 64-Array CPV Power Block**

| CABLE DISTANCE | | |
|---|---|---|
| | QTY. | L (m) |
| A | 4 | 142 |
| B | 4 | 130 |
| C | 4 | 118 |
| D | 4 | 106 |
| | | |
| | TOTAL DISTANCE: | 1984 |

### 4.3.2 GreenVolts CPV Array Installation Step 2: Drilling and Pouring Piers

**Figure 12: Drilling and Pouring Piers (5 per CPV array)**

As with other CPV and PV trackers, the specific pier design depends on the local soil conditions and needs of the particular application. Typically, the piers are designed by a licensed civil engineering firm to meet the applicable local and state code requirements. GreenVolts provides detailed static and dynamic loading specifications for its CPV arrays, which have been independently certified to comply with the California and International Building Codes (IBC).

Because of the distributed stanchions and relatively low profile of the GreenVolts CPV arrays, the piers are considerably smaller than those used by other CPV systems. This means less material and labor are required to install the piers for each MWp of generating capacity

GreenVolts CPV arrays can be installed on a wide range of piers and foundations, including:

- Concrete piers
- Raised concrete piers (for elevated deployments, e.g. parking lots)
- Hybrid piers (driven steel plus concrete)
- Driven or screw type steel piers
- Partial or full spread foundations

### 4.3.3 GreenVolts CPV Array Installation Step 3: Setting and Aligning Stanchions

**Figure 13: Setting and Aligning Mounting Stanchions (5 per CPV array)**

Once the AC distribution lines have been installed and the piers have been set, the GreenVolts CPV arrays can be rapidly installed using the array components which have been staged throughout the project site.

One particular advantage of the modular design of GreenVolts CPV arrays is that no heavy equipment is needed at the project site, which offers a major cost savings. As seen in the photos throughout this section, a Gradall telehandler (or similar) provides all the lifting capability needed to unload trucks and fully assembly the arrays.

Using progressive installation work flows, several small teams (3 or 5 people, including the Gradall operator), each dedicated to one or more of the installation steps, rapidly executes the installation, unit by unit, according to the installation work instructions and verification checks.

Array installation begins with hoisting, setting and aligning each stanchion.

This typically takes a team of three people only 7 minutes to complete per stanchion.

**Figure 14: Installed CPV Array Support Stanchions on Piers (Shown for Two Arrays)**

The photo above shows the installed stanchions for two GreenVolts CPV arrays. It also shows that only nine (9) stanchions are used in this case. This is an example of one stanchion being shared by two grouped arrays.

The use of shared stanchions within array groups (up to four arrays per group) enables a significant installation cost savings in both materials and labor. For example, considering a power block of 64 GreenVolts CPV arrays (see Appendix III):

**Table 3: Example Installation Unit Savings through Use of Shared Stanchions**

| Stanchion Configuration | Stanchions per Power Block |
|---|---|
| Without Sharing | 320 |
| Shared Stanchions (4X Array Groups) | 272 (a 15% reduction) |

### 4.3.4 GreenVolts CPV Array Installation Step 4: Assembling Roll Beam Sections

**Figure 15: Assembling a Roll Beam and Tilt Axle (4 per CPV Array)**

In parallel with the installation of the stanchions, the roll beams of the GreenVolts CPV array are assembled. To save space during shipping, the roll beams are received at the project site without the tilt axles attached. As shown in the figure above, each 6 meter long roll beam segment is supported off the ground and the two tilt axle halves are attached.

Also in parallel with this, after each stanchion is erected, the roll bearings (4 per array) and roll drive motor assembly (1 per array, atop center stanchion) are installed on top of the stanchions and aligned.

### 4.3.5 GreenVolts CPV Array Installation Step 5: Installing Roll Beam Sections

**Figure 16: Hoisting and Installing a Roll Beam/Tilt Axle Assembly (4 per CPV Array)**

As shown in the figure above, after each roll beam assembly is completed, it can be lifted by a Gradall and inserted into the roll bearings and attached to the roll drive motor.

A GreenVolts roll beam segment can typically be fully assembled, installed and aligned in about 45 minutes by a team of three people.

Once this point is reached, an array is now ready to receive its CPV paddle assemblies.

### 4.3.6 GreenVolts CPV Array Installation Step 6: Installing Factory-Assembled Paddles

**Figure 17: Installing a Factory-Assembled CPV Paddle (8 per CPV Array)**

As discussed above, GreenVolts CPV paddles (each holding 8 CPV modules) are shipped to a project site fully assembled and pre-wired. This makes installation very rapid and helps ensure high quality by minimizing the potential for field installation errors.

As can be seen in the figure above, each paddle is lifted by a Gradall and is guided on to the tilt axle by a ground crew. This allows the paddles to be quickly slid on to its axle and then locked into position.

Typically, a GreenVolts CPV paddle can be installed in 7 minutes by a team of five people.

**Figure 18: Installing a Factory-Assembled CPV Paddle – Another View**

After each paddle pair is installed on to the roll beam assembly, the tilt actuators are attached and the electrical connections to the factory assembled cable harnesses are made.

The figures below show two specific innovations developed by GreenVolts which significantly speed up and reduce the installation labor costs of GreenVolts CPV arrays: the paddle lifting bar and a hinged linear actuator mounting bracket. The lifting bar allows a paddle to be directly picked off its shipping pallet in a vertical orientation (see Appendix V), rotated over horizontally and slid onto its receiving tilt axle. The paddle never touches the ground once it leaves the factory.

**Figure 19: GreenVolts Paddle Lifting Bar (Yellow) – Paddle Vertically on Pallet**

**Figure 20: GreenVolts Paddle Lifting Bar (Yellow) – Paddle Horizontal For Installation**

Once both paddles on a tilt axle have been installed, their hinged curve bars (which were shipped lying flat to save space) are unfolded down, mechanically connected via a truss, and the linear tilt actuator is quickly and easily attached.

**Figure 21: GreenVolts Paddle Pair, Curve Bars and Attachment Truss**

### 4.3.7 GreenVolts CPV Array Installation Step 7: Hanging and Connecting the SCP

**Figure 22: Hanging and Connecting the System Control Point (SCP)**

The last step in installing a GreenVolts CPV Array is to hang and connect its GreenVolts system control point (SCP).

GreenVolts SCPs are received at the project site fully assembled, programmed and pre-tested. The electrical connections that are made to a given SCP are:

- 600 VDC connection to the two independent strings of CPV paddles (each string has its own independent MPPT) through its DC disconnect
- Roll motor and tilt actuator power supply cable harness
- Tracker actuation sensor cable harness
- AC disconnect

Once the AC disconnect is closed and AC power is supplied, the SCP boots up, it determines its location via the on-board GPS unit, it securely connects to the internet via the on-board Wi-Fi, and it autonomously configures itself per the instructions provided by GreenVolts Solar Operations Center. When all system checks are successfully completed, the array is ready to begin operation when instructed to do so.

### 4.3.8 Completed GreenVolts CPV Arrays

**Figure 23: Completed GreenVolts CPV Arrays – the Nearest Array Shows SCP and 480 VAC Disconnect**

## 4.4 GreenVolts Detailed Installation Cost Study

Over the period beginning in early 2009 and continuing through 2011, GreenVolts collected the installation cost figures from their CPV projects that were deployed across a wide range of locations with diverse site-specific layouts, terrain and soils conditions. The table below summarizes the significant scope of the projects which were included in this cost study.

**Table 4: Summary of the Project Scope in GreenVolts Installation Cost Study for the CEC PIER Project**

| | |
|---|---|
| **No. of GreenVolts Project Sites in Study** | 6 |
| **Total No. of CPV Arrays in Study** | 144 |
| **Total CPV Generating Capacity in Study** | 2.76 MWp |

## 4.5 GreenVolts CPV Installation Cost Breakdowns

**Figure 24a: GreenVolts Installation Cost Breakdowns**

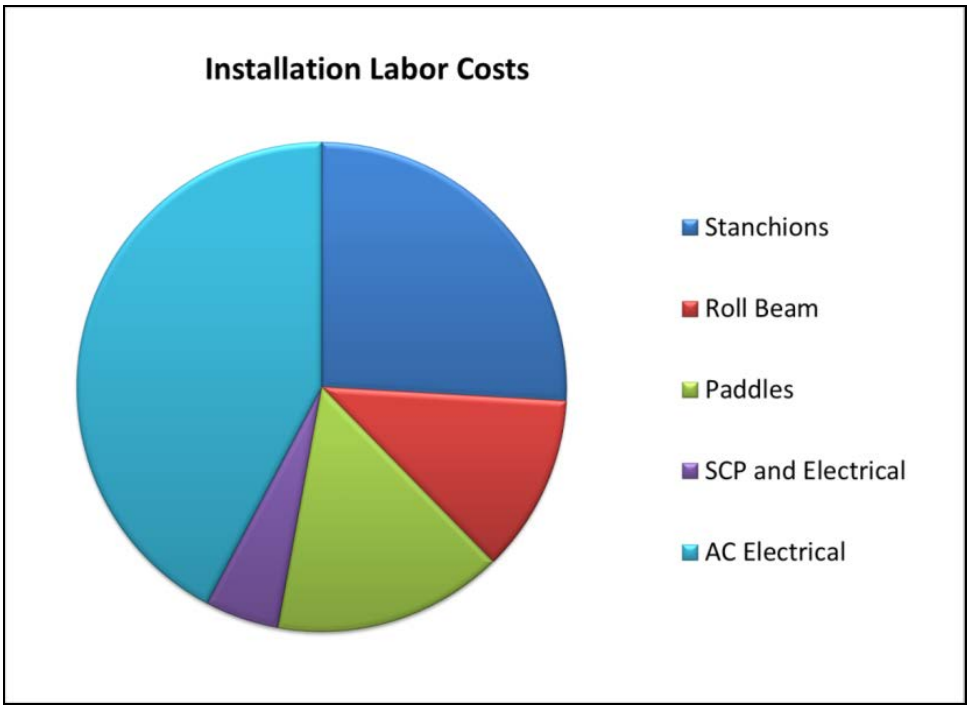


**Figure 24b: GreenVolts Installation Cost Breakdowns**

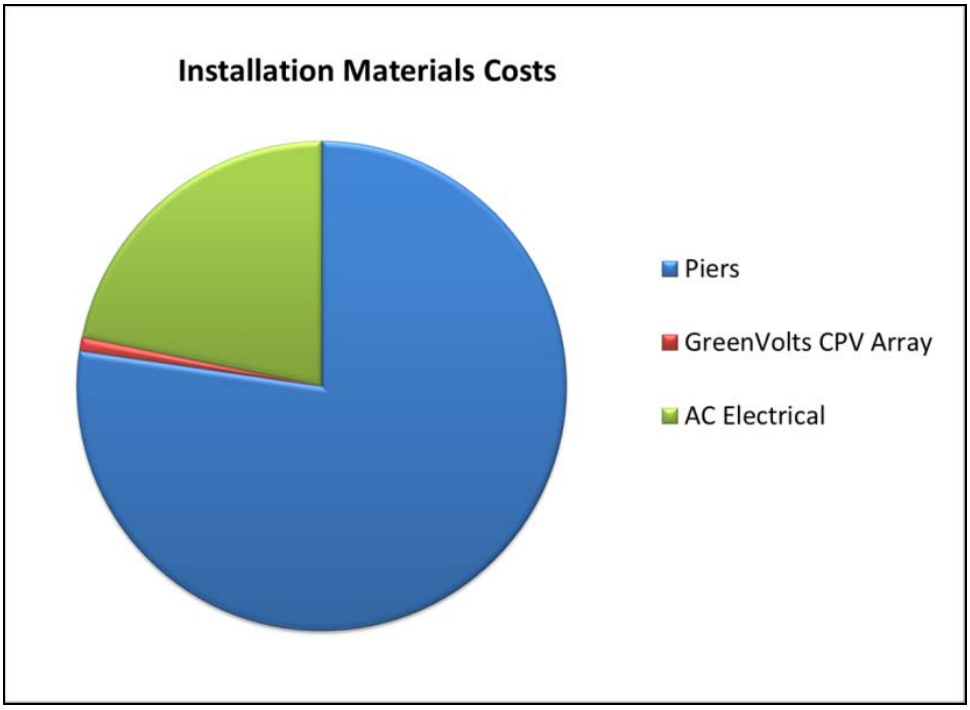
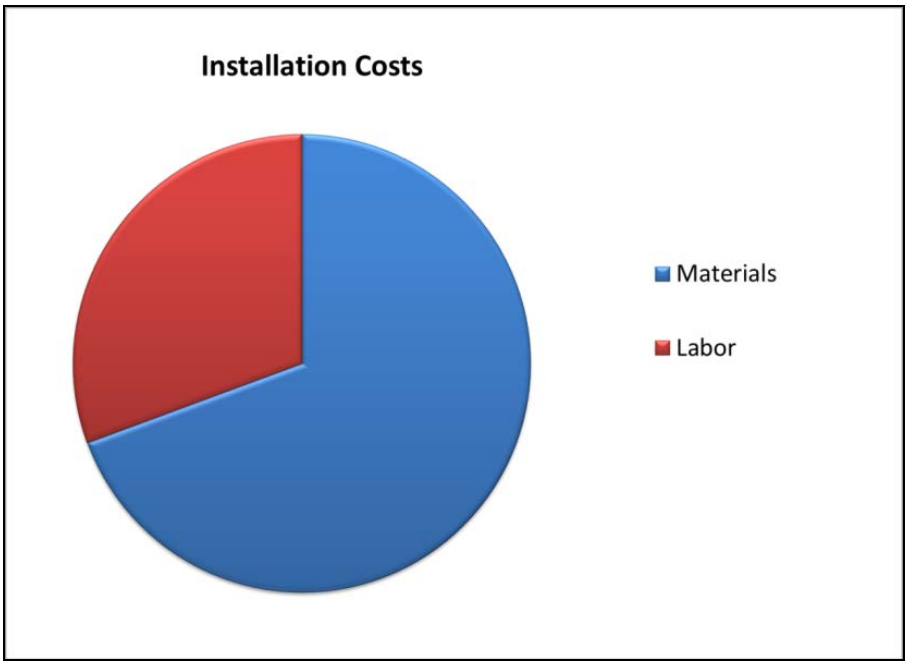



**Figure 24c: GreenVolts Installation Cost Breakdowns**



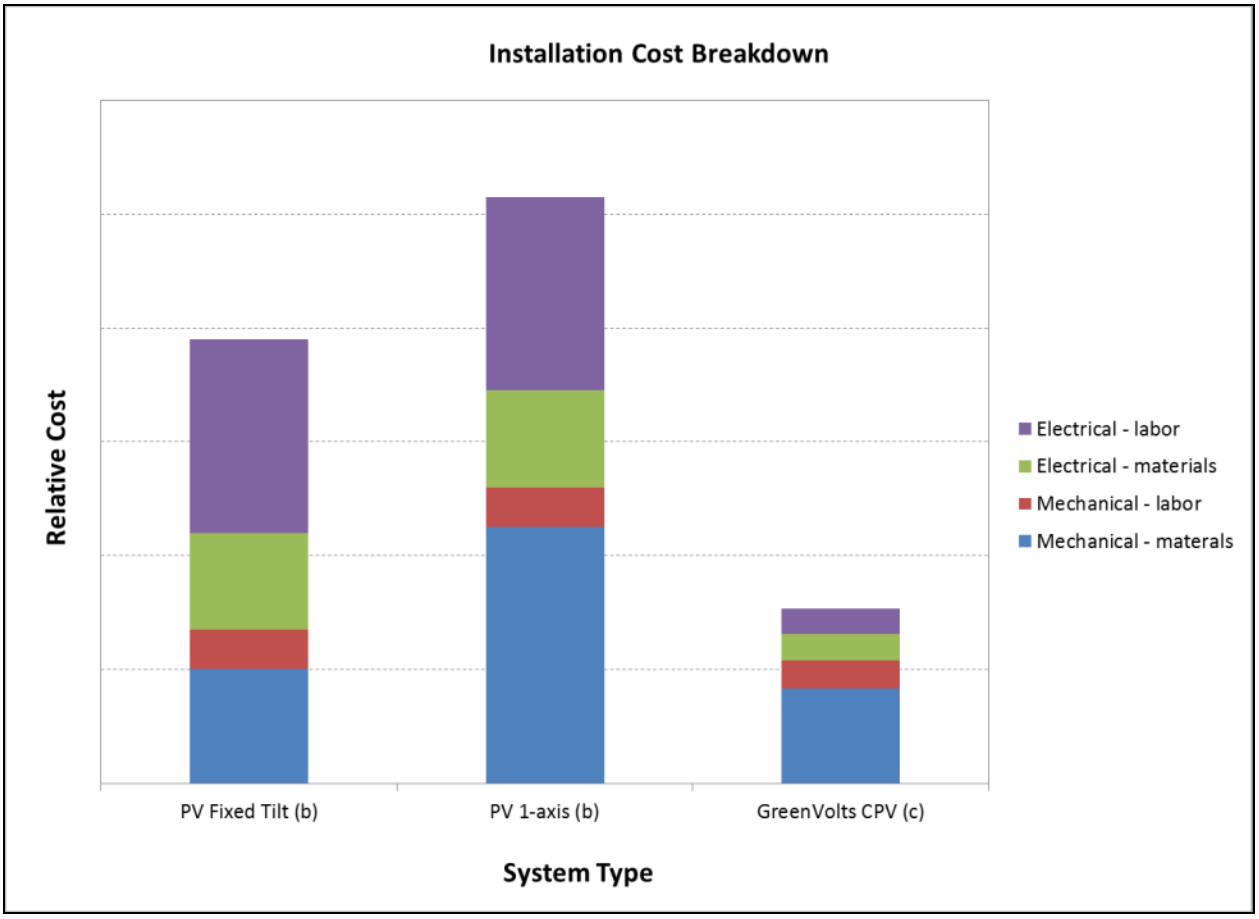

**Note:** Transformer (XFMR) and MVAC BOS are excluded because:

- They are Balance-of-Plant (BOP) equipment
- These costs are the same for PV and CPV systems
- These costs are not included in either the GTM or NREL cost data and models

**Source:** GreenVolts internal cost data.

## 4.6 Comparison between GreenVolts CPV and PV Installation Costs

**Figure 25: Comparison between GreenVolts CPV and PV Installation Costs**




**Note:**

(a) Includes: foundations, rack/tracker, module and inverter installation, DC and 480 VAC BOS. Does not include: Module and Inverter equipment costs, XFMR, MVAC BOS, or other BOP.

**Sources:** (b) NREL *Solar PV Manufacturing Cost Model Group: Installed Solar PV System Prices*, NREL/PR-6A20-50955, Feb. 2011 (c) GreenVolts internal cost data.

## 4.7 GreenVolts Speed of Installation Data

As described in Section 4, GreenVolts has developed

- A high performance CPV array architecture that is very materials efficient
- A comprehensive manufacturing and supply logistics strategy that is based on factory pre-assembly of all major CPV, mechanical and electrical components
- And a highly streamlined set of field installation processes that minimizes on-site labor

As a result, GreenVolts has been able to achieve industry leading CPV installation costs.

To validate these results, GreenVolts collected real installation data over 2010 – 2012, across six different large-scale installations throughout California, and totaling more than 144 GreenVolts CPV arrays (2.76 MWp).

The labor costs associated with the three of the main installation steps are:

- Hoisting, attaching and aligning support stanchions
- Assembling, hoisting and installing the roll beams
- Hoisting and installing the CPV paddles

Example costs of each of these steps are shown in the table below.

**Table 5: Speed of Installation of GreenVolts CPV Array Elements and Associated Labor Costs**

| | |
|---|---|
| kWp/Array | 19.2 |
| Arrays/Power Block | 64 |
| MWp/Power Block | 1.23 |
| $/Person.hr | $ 45.00 |

| | People on Crew | min/Unit | hr/Unit | Units per Array | Units per Power Block | Person.hr per Power Block | Person.hr per MWp | $/Wp |
|---|---|---|---|---|---|---|---|---|
| Stanchions | 3 | 7 | 0.117 | 5 | 320 | 112.00 | 91.15 | $0.004 |
| Roll Beams | 3 | 45 | 0.750 | 4 | 256 | 576.00 | 468.75 | $0.021 |
| Paddles | 5 | 7 | 0.117 | 8 | 512 | 298.67 | 243.06 | $0.011 |
| **Sutotal** | | | | | | 986.67 | 802.95 | $0.036 |

# CHAPTER 5: Conclusion

A number of significant conclusions can be drawn from the industry-leading innovations GreenVolts has developed and the successful results they achieved under their CEC PIER project.

## 5.1 Installation Materials Cost Reduction Opportunities

### 5.1.1 Distributed Array-Level Inverters

For CPV systems in particular, which require two-axis tracking arrays, the use of distributed array-level inverters provide an ideal opportunity to integrate all of the multiple electrical, control, monitoring and communications equipment into a single integrated multi-functional system control point. This, combined with only needing to run AC power distribution cables across the array field provides for higher performance and significantly reduced costs.

### 5.1.2 Distributed Modular Array Architecture

The distributed structure of GreenVolts CPV arrays enable the use of smaller mounting piers and eliminates the need for heavy equipment on site.

### 5.1.3 Wireless Communications

The use of Wi-Fi eliminates the need to run local area network (LAN) cables in the array field.

## 5.2 Installation Labor Cost Reduction Opportunities

### 5.2.1 Factory Pre-Assembly

Performing as much pre-assembly at the factory as possible provides a number of important benefits and cost reductions: faster installation, higher quality (fewer errors) and less waste.

### 5.2.2 Design for Shipping and Site Logistics

As above, the modular architecture of GreenVolts CPV arrays have been specifically designed to efficiently fit into standard shipping containers which are loaded to optimize the on-site staging of array components to increase the speed installation and reduce labor costs.

### 5.2.3 Distributed Modular Array Architecture

Similarly, the design of GreenVolts CPV arrays enables the use of smaller and fewer installation teams that are specifically trained to rapidly erect arrays in an assembly line like manner.

## 5.3 Broad Applicability to Other CPV and PV System Architectures

The design principles that formed the basis for the innovations that GreenVolts developed for its CPV Arrays are not limited only to their systems and projects, but can also be utilized by other CPV and PV system designers and project developers to achieve similar results. This will greatly expand the scope of benefits to the solar industry and significantly reduce costs to customers of large-scale solar energy.

# CHAPTER 6: Recommendations

The GreenVolts CPV array, which incorporates the proven cost reductions achieved under their CEC PIER project, has proven successful in California and elsewhere.

GreenVolts recommends that other CPV and PV system vendors consider utilizing similar design principles to achieve their own significant cost reductions. If this is done, it will bring the cost reduction advantages that GreenVolts has achieved to a much broader market and increase the overall benefit to the industry and the customer.

Based on GreenVolts demonstrated success in meeting the goals of this CEC PIER project, it is also recommended that new CPV system designs be developed that leverage the fundamental concepts developed by GreenVolts across a wider range of vertical markets and specific applications.

This will further reduce the installation cost of CPV power generation, attract new investors to develop and deploy CPV power plants at the commercial, industrial and utility scales, and thereby in turn, increase the overall benefit to California ratepayers.

GreenVolts also recognizes that there is considerable room for additional refinements and new innovations that will continue further reduce the installation costs of CPV systems. GreenVolts will be aggressively pursuing these opportunities and recommends that other system designers do as well, to continuously improve the competitiveness of CPV and maximize the benefit to both Californians and all customers of solar energy.

# CHAPTER 7:
# Public Benefits to California

GreenVolts innovations and successful achievements under its CEC PIER project to *Reduce the Installation Cost of Concentrating Photovoltaics* will provide significant benefits to a wide range of stakeholder groups throughout the CPV industry in California (and elsewhere), including:

- Equipment manufacturers
- Solar project developers
- Solar project investors
- Project EPC and ongoing service provides
- Other CPV and PV system developers
- Commercial and industrial power customers
- State and local municipalities
- Electric power utilities and system operators
- California ratepayers
- Construction employees building new and larger CPV plants

There will be many public benefits to California that will be derived from GreenVolts efforts and solutions, including:

- Reduced time to install CPV systems
- Elimination of the need for expensive heavy equipment to install CPV systems
- Less disruption to the land where CPV projects are sited
- CPV projects that can be sited in locations with a wider range of soil and terrain conditions
- Higher Return on Investment (ROI) for investors in CPV projects
- Increased adoption of CPV projects as part of California's overall Renewable Portfolio
- Reduced electricity rates for California rate payers
- Reduced dependency on non-renewable forms of energy

# REFERENCES

[1] GTM Research, Solar PV Balance of System (BOS): Technologies and Markets, June 2011, graphic retrieved (March 2012) from: http://www.greentechmedia.com/research/report/solar-pv-bos-2011

[2] K. Branker et al., A Review of Solar Photovoltaic Levelized Cost of Electricity, Renewable and Sustainable Energy Reviews 15 (2011) 4470– 4482

[3] A. Goodrich et al., Solar PV Manufacturing Cost Model Group: Installed Solar PV System Prices, Electronics in Photovoltaic Systems Workshop, NREL/PR-6A20-50955, February 8, 2011

[4] California DNI map retrieved (March 2012) from: http://www.nrel.gov/gis/pdfs/eere_csp/eere_csp_h_california.pdf

# GLOSSARY

| Acronym | Full Name |
|---|---|
| AC | Alternating Current |
| BOP | Balance of Plant (materials and equipment) |
| BOS | Balance of Systems (materials and equipment) |
| CPV | Concentrating Photovoltaics |
| DC | Direct Current |
| DNI | Direct Normal Irradiance (W/m2 – intensity of sunlight usable by CPV) |
| FRU | Field Replaceable Unit |
| HCPV | High Concentration Photovoltaics |
| ISIS | GreenVolts Intelligent Solar Information System |
| kWh | Kilowatt hours (an amount electrical energy produced over a period of time) |
| kWac | Kilowatts AC (An AC nameplate rating of installed equipment) |
| LAN | Local Area Network |
| LCOE | Levelized Cost of Electricity ($/kWh) |
| LV | Low Voltage (up to 1000 VDC, 480 VAC) |
| MVAC | Medium Voltage AC (above 480 VAC) |
| MW | Megawatt (a level of electrical power being generated at a moment in time) |
| MWh | Megawatt hours (an amount electrical energy produced over a period of time) |
| MWp | Megawatt Peak (a DC nameplate rating of installed equipment) |
| PV | Photovoltaic |
| ROI | Return on Investment |
| SCP | GreenVolts system control point |
| Wp | Watts Peak (a DC nameplate rating of installed equipment) |
| XFMR | Transformer |

# APPENDIX A:
# The Levelized Cost of Electricity (LCOE)

For an electrical energy producing facility that operates over a lifetime of $T$ years, the Levelized Cost of Electricity ($LCOE$) for that facility is defined to be the constant (i.e. levelized) rate of electricity [$/kWh] that the facility will need to be able to charge for the electricity it produces to exactly meet all of the costs incurred over its operating lifetime.

In this regard, the LCOE of a given generating facility represents a breakeven point, and as such, provides an important metric when evaluating the economic competitiveness of both conventional and renewable energy projects.

For each operating year $t$ [$0 \ldots T$], if the amount of energy produced is $E_t$ [kWh], and the total costs incurred are $C_t$ [$], then the $LCOE$ is defined as

$$\sum_{t=0}^{T}\left(\frac{E_t}{(1+r)^t} \times LCOE\right) = \sum_{t=0}^{T}\frac{C_t}{(1+r)^t} \tag{1}$$

where $r$ [%] is the discount rate on future cash flows. Rewriting equation (1) yields

$$LCOE = \frac{\sum_{t=0}^{T}\frac{C_t}{(1+r)^t}}{\sum_{t=0}^{T}\frac{E_t}{(1+r)^t}} \tag{2}$$

The total cost $C_t$ in year $t$

$$C_t = Q_t + I_t + O_t + M_t + F_t \tag{3}$$

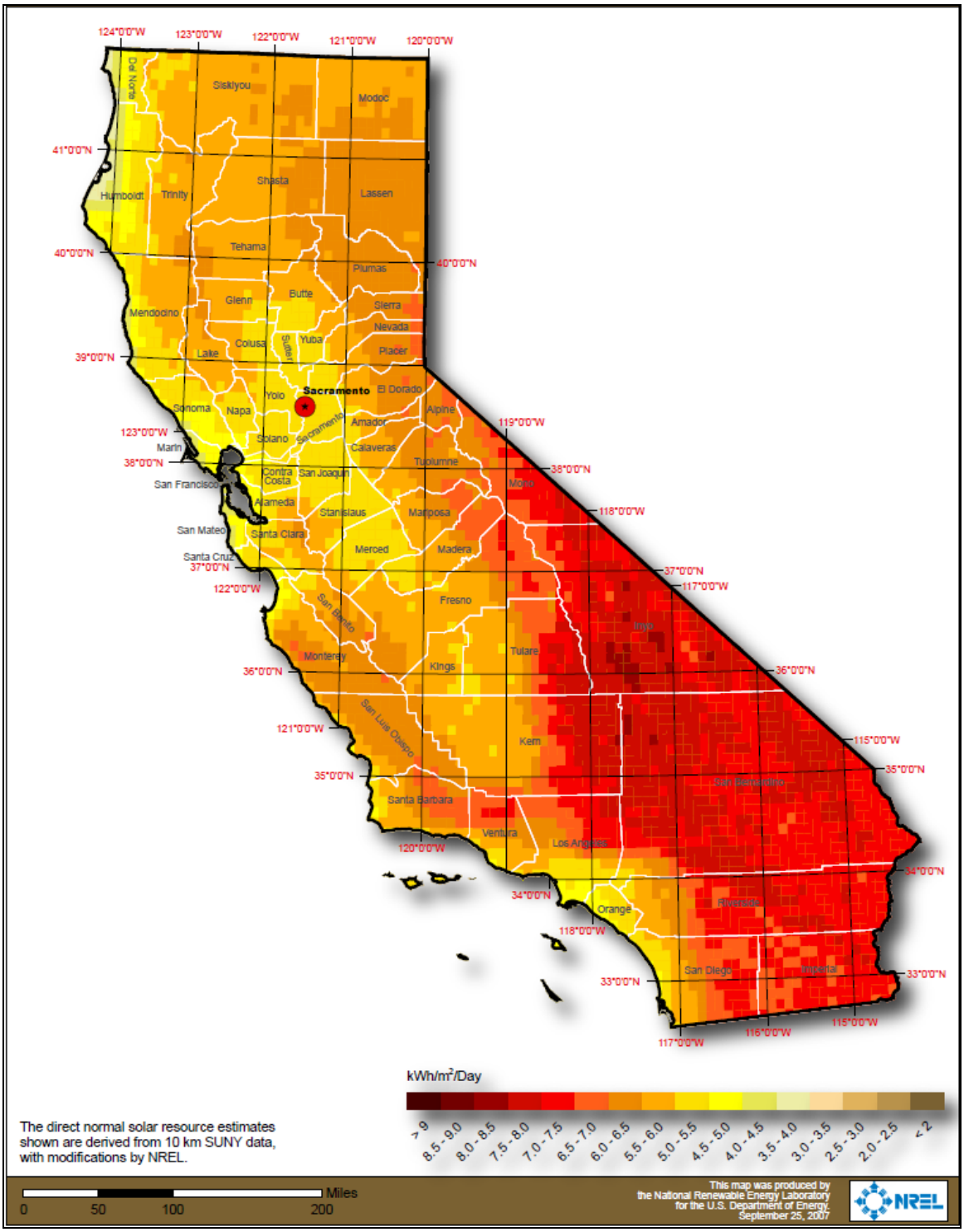
is the sum of: the equipment costs $Q_t$, the installation costs $I_t$, the operating costs $O_t$, the maintenance costs $M_t$, and the financing costs $F_t$. The energy $E_t$ produced in year $t$ is often expressed as degraded ratio of the rated energy production $S_t$ of the facility at the start of its operating lifetime

$$E_t = S_t(1-d)^t \tag{4}$$

where $d$ [%] is the annual degradation rate.

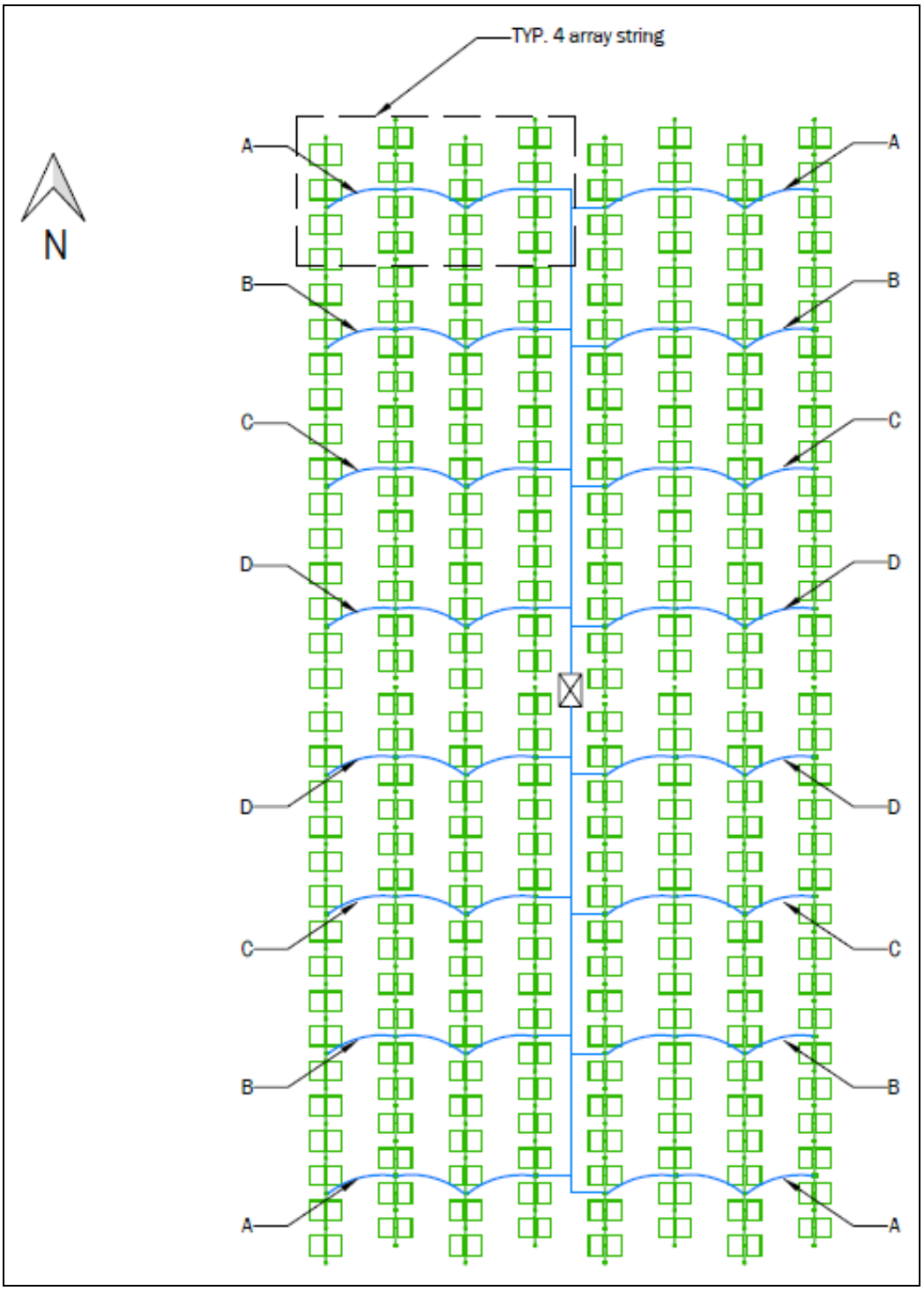
# APPENDIX B:
# Direct Normal Irradiance Map of California

Figure B1: DNI Map of California from NREL [4]



# APPENDIX C:
# GreenVolts Reference CPV Power Block – 1.229 MWp

Figure C1: GreenVolts Reference 64 Array CPV Power Block Layout



# APPENDIX D:
# Example GreenVolts CPV Installations

GreenVolts CPV Installation in Fremont, CA

Figure D1: GreenVolts CPV Arrays in Fremont, CA

| | |
|---|---|
| **Location** | Fremont, California |
| **Date of Completion*** | May 2011 |
| **Number of GreenVolts CPV Arrays** | 5 |
| **Power Plant Capacity** | 80 kW |

* Completion of last array. GreenVolts arrays operating continuously at this location since December 2010.

GreenVolts CPV Installation in Byron, CA

Figure D2: GreenVolts CPV Arrays in Byron, CA

| | |
|---|---|
| **Location** | Byron, California |
| **Date of Completion** | June 2011 |
| **Number of GreenVolts CPV Arrays** | 20 |
| **Power Plant Capacity** | 320 kW |

# APPENDIX E:
# GreenVolts CPV Dual Use Installations

Figure E1: Elevated GreenVolts CPV Arrays Used in Shaded Parking Lots

Figure E2: GreenVolts CPV Arrays Used in an Agricultural Application

# APPENDIX F:
# GreenVolts Solutions for Low Cost Logistics

Figure F1: Factory Pre-Assembled, Ready-to-Install GreenVolts CPV Paddles on Shipping Pallet

Figure F2: Bundled GreenVolts CPV Paddles Delivered to Site

Figure F3: Pre-staged GreenVolts CPV Paddles for Rapid Installation

# APPENDIX G:
# GreenVolts Detailed Installation Cost Data

Table G1. Roll Up of DETAiled GreenVolts installation Materials and Labor Cost Data

| **GreenVotls Installation Costs Data** | | (a) |
|---|---|---|
| **Material Costs** | | $/Wp |
| Piers/Foundation | $ | 0.165 |
| Stanchion, Roll Beam, Paddle | $ | 0.002 |
| AC Electrical (not including XMFR & MVAC BOS) | $ | 0.046 |
| **Material Subtotal** | **$** | **0.213** |
| **Labor Costs** | | $/Wp |
| Piers/Foundation | $ | - |
| Stanchions | $ | 0.024 |
| Roll Beam | $ | 0.011 |
| Paddles (with modules) | $ | 0.014 |
| SCP, DC Electrical & ORT | $ | 0.005 |
| AC Electrical (not including XMFR & MVAC BOS) | $ | 0.040 |
| **Labor Subtotal** | **$** | **0.094** |
| **Installation Cost Total** | **$** | **0.307** |

**Note:** Transformer (XFMR) and MVAC BOS are excluded because:

- They are Balance-of-Plant (BOP) equipment
- These costs are the same for PV and CPV systems
- These costs are not included in either the GTM or NREL cost data and models

**Source:**(a) GreenVolts internal cost data.

# APPENDIX H:
# Comparison between GreenVolts CPV and PV Installation Costs

Table H1: Comparison between GreenVolts CPV and PV Installation Cost Data

| **Installation Cost Data** (a) | PV Fixed Tilt (b) [$/Wp] | PV 1-axis (b) [$/Wp] | GreenVolts CPV (c) [$/Wp] |
|---|---|---|---|
| **Installation Materials** | | | |
| Mechanical | 0.20 | 0.45 | 0.17 |
| Electrical | 0.17 | 0.17 | 0.05 |
| **Subtotal** | **0.37** | **0.62** | **0.21** |
| **Installation Labor** | | | |
| Mechanical | 0.07 | 0.07 | 0.05 |
| Electrical | 0.34 | 0.34 | 0.04 |
| **Subtotal** | **0.41** | **0.41** | **0.09** |
| **Total** | **0.78** | **1.03** | **0.31** |

**Note:**(a) Includes: foundations, rack/tracker, module and inverter installation, DC and 480 VAC BOS. Does not include: Module and Inverter equipment costs, XFMR, MVAC BOS, or other BOP

**Sources:** (b) NREL *Solar PV Manufacturing Cost Model Group: Installed Solar PV System Prices*, NREL/PR-6A20-50955, Feb. 2011 (c) GreenVolts internal cost data.

# APPENDIX I:
# Additional GreenVolts Installations

GreenVolts CPV Installation in Mecca, CA

Figure I1: GreenVolts CPV Arrays in Mecca, CA

| | |
|---|---|
| **Location** | Mecca, California |
| **Date of Completion** | June 2011 |
| **Number of GreenVolts CPV Arrays** | 1 |
| **Power Plant Capacity** | 16 kW |

GreenVolts CPV Installation in San Dimas, CA

Figure I2: GreenVolts CPV Arrays in San Dimas, CA

| | |
|---|---|
| **Location** | San Dimas, California |
| **Date of Completion** | January 2012 |
| **Number of GreenVolts CPV Arrays** | 31 |
| **Power Plant Capacity** | 496 kW |

GreenVolts CPV Installation in Redding, CA

Figure I3: GreenVolts CPV Arrays in Redding, CA

| | |
|---|---|
| **Location** | Redding, California |
| **Date of Completion** | December 2011 |
| **Number of GreenVolts CPV Arrays** | 18 |
| **Power Plant Capacity** | 288 kW |

GreenVolts CPV Installation in Yuma, AZ

Figure I4: GreenVolts CPV Arrays in Yuma, AZ

| | |
|---|---|
| **Location** | Yuma, Arizona |
| **Date of Completion** | October 2011 |
| **Number of GreenVolts CPV Arrays** | 64 |
| **Power Plant Capacity** | 1024 kW |