# Streamlining Large Scale Photovoltaic Arrays for Utility Interconnection

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***Abstract*-- This paper provides an analysis of the feasibility of moving large scale photovoltaics (PV) closer to grid parity by reducing significant balance of system costs associated with medium voltage grid interconnection. Inverter costs have been reduced considerably over the last few years, reducing one of the larger costs in the interconnection of large scale systems. This research focuses on the medium voltage interconnection piece of the puzzle, developing a cost and equipment comparison based upon two divergent approaches currently acceptable to utilities in interconnecting such systems. The first being based on the Pennsylvania Electric Co. interconnection standards for new service, and the second is based on Atlantic City Electric's overhead standards for new service. This research explores the noteworthy differences between these systems, and their effects on making large scale PV power plants more economic.**

***Index Terms*— Interconnection, electric utility, renewable power systems, large-scale, photovoltaics, economics.**

## I. Introduction

THIS research paper provides a detailed equipment and cost comparison of two utility scale photovoltaic systems of approximately equal size. The first of the two systems is representative of an existing 3MW system that was recently commissioned in the U.S.; the second system is based upon final engineering drawings and interconnection specifications, procurement information and basic wiring designs that were previously completed by the authors. The location (region) for which these system costs are accurate is in the northeastern portion of the U.S. Both systems rely on some of the largest DC to AC inverters currently on the market, 500kW inverters from Satcon or Xantrex, as well as comparably sized transformers and switchgear. Our analysis provides an in-depth overview of each plants' sub-systems – namely the necessary switchgear, transformer, metering and safety equipment for interconnection to the utility. The research we completed provides a meaningful comparison pointing out stark contrasts in design and key capital investment items. The ability to make such large scale systems financially viable and easily replicable relies in large part on controlling the costs of these integral parts. In the United States costs per kilowatt-hour of fuel delivered power to the grid ranges between three to five cents for nuclear and coal power and more for oil and natural gas (5-25 cents/kWh) dependent on current fuel prices. Large scale PV systems are currently in the 30-50 cent/kWh range, making PV significantly more expensive. With a wide variety of advancements in technology, a significant reduction in the price of PV materials may reach the U.S. Department of Energy estimate of $1-2 per Watt in the next decade. The greater part of the costs associated with the DC side of such systems lies in these module and racking costs, with only moderate cost savings achievable by wiring optimization. For this reason the authors focus on comparisons of alternative AC side designs for medium voltage interconnection from the DC to AC inverters onward, as much of this initial investment may be significantly reduced based upon interconnection voltage and overhead vs. underground design decisions.

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## II. System Overviews and Comparison

The following sections provide a detailed overview of each sub-system of the two designs, pointing out all of the major differences encountered. A direct comparison of approximate costs, components utilized, and single lines (starting with the larger of the two systems), is also given.

### *A. 3MW*

The major components used in the design of the 3MW system are given in Table I. By using the largest available PV inverters at the time, only six were necessary to create the first step in interconnecting to the utility grid. The premium in price of two 500kVA transformers over a single 1MVA transformer is quite substantial, enough so that the introduction of switchgear equipment to connect two inverters to feed one transformer still provided substantial cost savings in equipment component and labor prices. The basic design relies on six pad mounted DC to AC inverters (and accompanying low voltage switchgear), three pad mounted 1MVA transformers, medium voltage 34 kV) switchgear on a separate pad, and a final set of cutouts and safety equipment to connect the PV array to the utility. This means that the PV array is essentially divided into three independent sections, each feeding a nearby combination of inverter and transformer pads which are combined only at the medium voltage switchgear and metering near the riser pole. All components are served underground until the final riser pole interconnects with utility's 34 kV overhead feeder.

### *B. 2MW*

This PV system setup shares many common elements with the underground 3MW design. Four independent DC sections (500 kVA each) in the PV array each feed their own 500 kW DC to AC inverter, all of which are then combined to feed a single interconnection to the grid. The stark difference in this with regard to the previous design lies in its effective use of less complex and more economic overhead equipment, allowing for overall fewer interconnection components.

Similar to the previous system, half megawatt sections of PV are connected to 500kW inverters, but in this system each sub-section uses their own 500kVA step-up (480V to 12kV) transformer. We encounter the first major difference of the two designs with the selection of the inverters. Some newly developed inverters have the option of being ordered without preexisting isolation transformers, which will not only save on costs but increase efficiency as well. While the need to physically isolate the system from the utility grid still exists, this job is now left to be completed by the step-up transformers. A seemingly natural step in reducing equipment, given that each of the 500kVA units already isolate the inverters from the grid. The four step-up transformers are combined by connecting them in loop-feed fashion to the metering equipment, after which the final switchgear is located on the utility pole.

### C. *Contrasts*

*1)* Overall *Cost Comparison:* By comparing the two approaches we immediately notice that simplicity of design and a reduction of necessary equipment is possible by giving the step-up transformers its more resourceful role. An approximate cost for the 3MW and 2MW systems is found in Tables I & II respectively. Input from utility engineers in the area has also given an insight into possible savings with the sort of economies of scale that an average sized utility would experience.

TABLE I
3MW SYSTEM EQUIPMENT LIST

| QTY | Equipment | Total Price (USD) |
|---|---|---|
| 6 | 500kW Satcon Inverters | 880,000 |
| 1 | Puffer Gas Switch & 4-Way Triad | 180,000 |
| 3 | 1MVA Cooper Transformers | 110,000 |
| 3 | Square D low voltage Switchgear | 40,000 |
| | Wire, Connectors & Conduit | 11,000 |
| 8,100ft | 1/0 Al Primary cable | 17,000 |
| 1,800ft | 600 Copper cable | 17,000 |
| | Pole & Feeder upgrades | 30,000 |
| | **Total:** | **1,285,000** |

TABLE II
2MW SYSTEM EQUIPMENT LIST

| QTY | Equipment | Price (USD) |
|---|---|---|
| 4 | 500kW Satcon Inverters | 600,000 |
| 4 | 500kVA Cooper Transformers | 62,000 |
| | Wire, Connectors & Conduit | 4,500 |
| 4000ft | 1/0 Al Primary cable | 8,200 |
| 320ft | 600 Copper cable | 3,000 |
| | Pole-top Cutouts & Safety Equip. | 2,700 |
| | **Total:** | **680,400** |

*2) Inverters to Step-up Transformers:* Inspection of the design for the 3MW system reveals the three inverter pads, each with two (2) Satcon inverter units (NOTE: these devices come with built in isolation transformers). From the inverters we are connected to the local Square-D switchgear in three-phase with six 600kcmil copper conductors and a single 1/0 ground conductor. From this switchgear twelve 600kcmil copper cables along with one 3/0 ground are routed to the 1MVA step-up transformer. This transformer is also mounted on its own cement pad to meet grounding requirements and to reduce settlement. These transformers will step the 480V three phase WYE up to the necessary 34.5kV to interconnect with the utility overhead. Coming out of the transformer we have three 1/0 aluminum conductors with concentric neutrals, all of which are buried in a trench spanning the distance from each of the transformer pads to the main switchgear pad. These cable lengths are ca. 1300ft, 900ft and 400ft for the three pads, for a total of 7800ft. By this point in the design it is obvious that the medium voltage underground setup has become quite involved, a factor which is clearly reflected in its installation costs. Fig. 1 gives us a single line diagram for this section of the system.

In the comparable portions of the 2MW design we notice the lack of a built-in isolation transformer in the DC to AC inverters. For relatively large systems such as these, a transformer may add up to about 1% of losses, which would account for about 6MWh per year for each of these inverters. Obviously not a trivial amount, especially when we consider the sort of renewable energy credits commonly traded in the U.S. at the time. Each MWhr accounts for one of these credits, which may have sold upwards of $600 each in the state of New Jersey [1], while alternative compliance payments by the utility have been in the $700/MWhr range [2]. This further stresses the need to reduce possible losses in these systems, as seemingly insignificant losses can quickly add up to large sums of money over the 30 year + life of these projects.

The other major difference in this part of the two designs is the fact that each inverter is coupled with its own step-up transformer in the 2MW design. There is a strong likelihood that if 1MW inverters been available at the larger array's time of conception (as they are now [3][4]) it might well have been designed to utilize one such large inverter per step-up transformer. This would have eliminated the local switchgear saving tens of thousands per inverter pad, decreased overall losses and saved even more on the purchase of a single large inverter versus buying two of smaller capacity. Fig. 2 shows the 2MW single-line diagram.

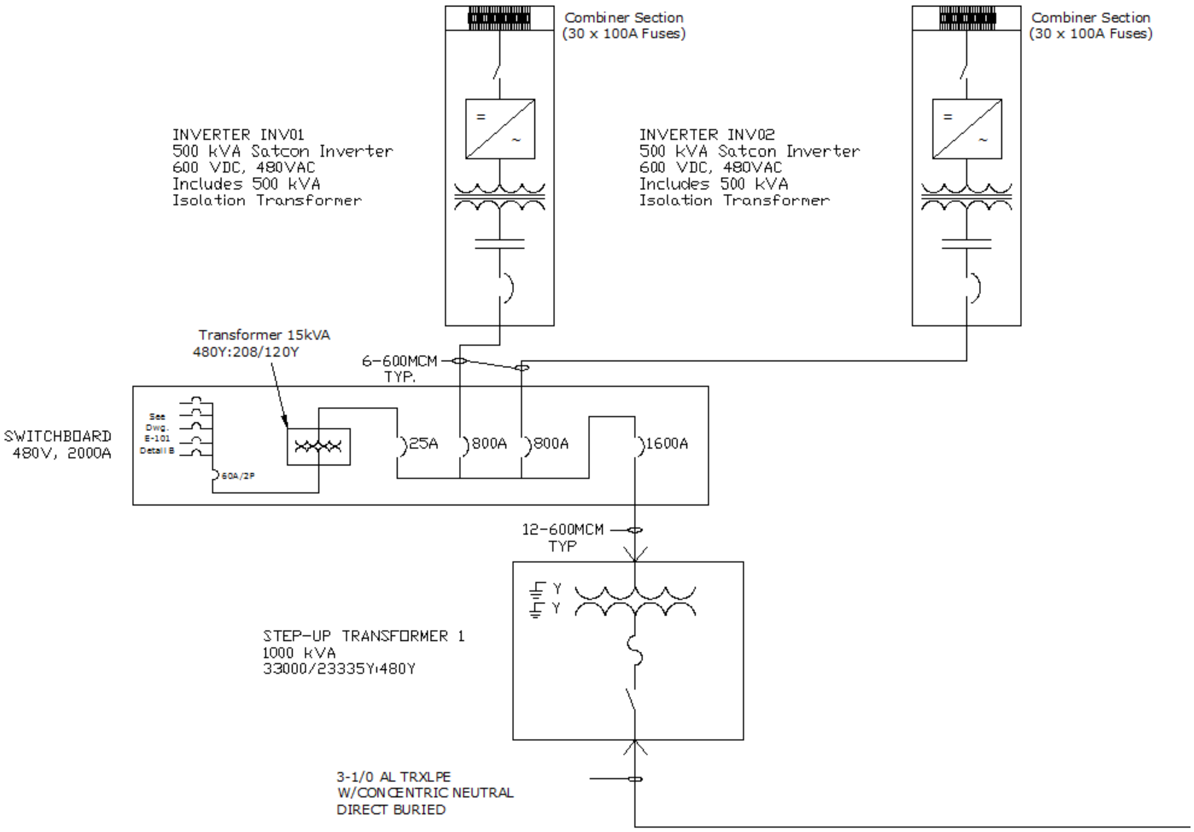


Fig. 1. Inverter to Step-up Transformer Single-line Diagram for the 3MW System

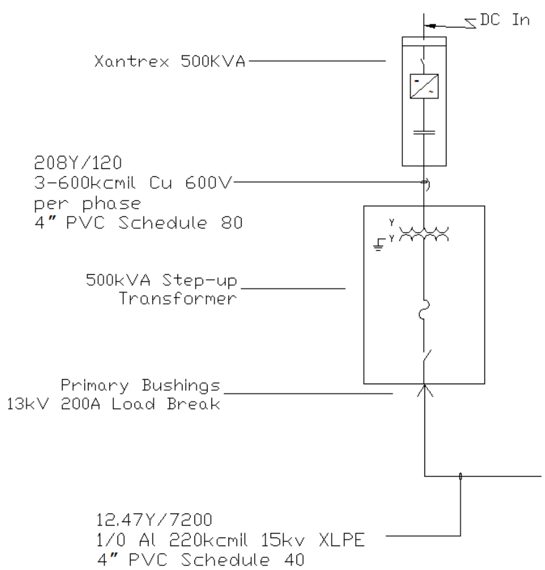


Fig. 2. Inverter to Step-up Transformer Single-line Diagram for the 2MW System

*3) Transformers and Switchgear:* Here the major difference in the two systems lies in the methods in which they combine multiple incoming feeds to be connected to the utility. The 3MW design called for several large switchgear units that take all nine (three per phase) conductors and combine them into a single set of three-phase to be metered and then fed into the utility. The first of which being the 4-way triad switch, which takes care of combining the three separate incoming three-phase feeds into a single set of three 1/0 copper cables and a 2/0 copper ground. This $SF_6$ gas insulated set of switches is then connected to the metering cabinet, which holds both PECO and PJM metering equipment. After being metered, the feed is connected to a large puffer gas switch, which takes care of the final interconnection before the pole. Elbow-arresters are used to connect the final set of cables to the pole, where we have a utility owned group of standard cutouts and lightning protection gear.

To forego the costs associated with these expensive units, the 2MW design has taken a "daisy-chain" approach with the transformers, also known as loop-feed, to combine each section of the array. In essence, transformers in such a loop-feed have the capability of remaining energized while local power generation can be halted. This means that the setup eradicates the need for a switch before metering, while leaving the possibility of disconnecting each sub-system individually for maintenance intact. Specifying transformers to come in a loop-feed design is a common option by manufacturers, and thus does not involve any premium in cost. We also save additionally on the lightning protection for the system. Only a single set of lightning arresters is needed on the final transformer of the 2 MVA system, after which standard metering equipment may be used to keep track of the energy being generated.

Finally, in the interconnection portions of the systems lies their greatest difference. Fig. 3 provides the single-line diagram for the main switchgear pad of the 3MW system, and

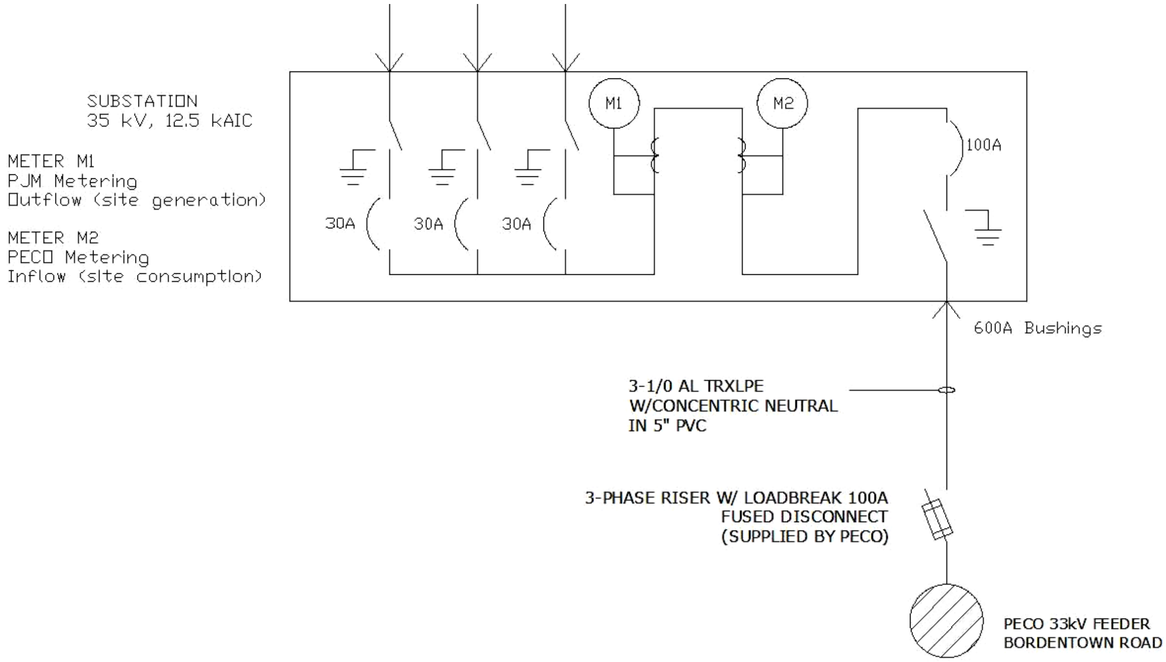


Fig. 3. 3MW Switchgear Single-Line Diagram

Fig. 4 the 2MW single-line from the final transformer to the utility line. As mentioned previously, the large switchgear pad was designed for the 3MW system to incorporate the 4-way triad switch, metering cabinet and final puffer switch. These units accounted for approximately a third of the entire equipment cost on the AC side of the system. The main reason we have such large switchgear is to eliminate any safety issues when connecting the incoming 33kV to the system. However, utility regulations require additional cutouts on the pole to give utility workers the ability to disconnect the system at any point in time, as well as fusing for the safety of the overhead. This means that after all of these expensive combiners and switches we still have additional switchgear and safety equipment on the utility pole. The streamlined 12kV design eliminates this equipment and makes use of the required components on the utility side to their full extent. Fused cutouts, being the only necessary switchgear, can be placed on the existing utility pole along with the desired metering equipment.

*D. Economics*

The cost data estimated in Tables I & II are for equipment only and do not incorporate any of the overheads and costs associated with the engineering design and labor for the installation of each of these systems. The estimates for project management and engineering fees for the purpose of this research were projected to be 10% of all equipment and setup. Stores and overheads for the items not to be directly shipped to the construction site were estimated to be 30% of their cost. Finally, installation costs for wiring and running conduit are generally expected to be around 100% of the materials' price. This creates a total cost estimate of about $224,000 for the larger 3MW system, and $95,000 for the smaller 2MW design. Approximately $40,000 of the larger amount represents the setup and installation of the inverter pad and main switchgear components. The total procurement, installation, management and design costs associated with the AC side of the 3MW will then have come to a total of approximately $1.5 Million, or 50¢/Watt. For the 2MW we come to a total of $775,000 which converts to about 39¢/Watt. An impressive 22% reduction in costs, which when applied to such large systems can cut investment by several hundred thousand dollars. Much of the savings came with the elimination of the bulky switchgear, which added up to almost $300,000 in end costs but we are largely convinced that even more savings can be uncovered, including installation costs, by the simplification of these systems using the design alternatives we have proposed where

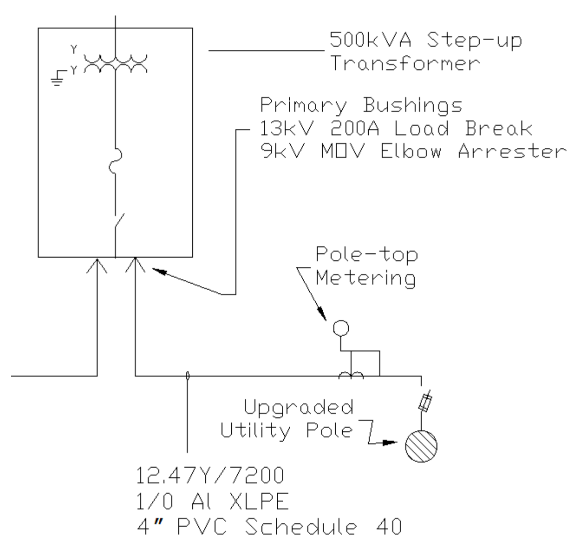


Fig. 4. 2MW Final Inverter & Interconnection Single-Line Diagram

highly complex parts are replaced with few major parts making way for much more rapid installations. Such an approach will lead to system prices that are controlled almost entirely by the commodity costs at the time. Total net costs for PV materials for commercial sized systems in the U.S. has dropped significantly over the past few years, having averaged below 4$/W in 2007 [5], a downward trend which should continue over the next few years.

By taking a simplistic and more minimalist approach to the design of large utility scale photovoltaic arrays, we have uncovered an 11¢/Watt (22%) savings for the AC interconnection portion of the system. System complexity was reduced significantly which will further reduce installation costs (not accounted for herein), and modularity of the AC side has also increased. Future site owners will have little difficulty in adding additional arrays to an existing interconnection, since the connecting of step-up transformers (and with that inverters) is done through the daisy chain approach of a loop-feed setup. In areas where the local utility regulations allow it, utilizing these types of savings will keep investments to a minimum and increase value for the owner.

## III. Acknowledgment

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## IV. References

[1] NJ Clean Energy (2009). SREC Trading Statistics Reporting Year 2009, NJBPU, Newark NJ,
[Online] Available: http://njcleanenergy.com/renewable-energy/programs/solar-renewable-energy-certificates-srec/pricing/pricing

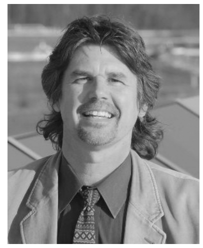
[2] NJBPU, "In the Matter of the Renewable Energy Portfolio Standards – Alternative Compliance Payments and Solar Alternative Compliance Payments", NJBPU, Newark, NJ, EO0610744, Sept. 2008

[3] Satcon, PowerGate Plus 1MW Commercial Solar PV Inverter, [Online] Available:
http://www.satcon.com/downloads/Satcon_PowerGate_Plus_1MW_300dpi.pdf

[4] SunEnergy, SunEnergy - Grid Connect, [Online] Available: http://www.sunenergy.com.au/pdf/GridConnect_US.pdf

[5] R. Wiser, G. Barbose, and C. Peterman., "Tracking the Sun: The Installed Cost of Photovoltaics in the U.S. from 1998-2007" Lawrence Berkley National Laboratory, Berkley, CA, LBNL-1516E, Feb. 2009

## V. Biographies



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