The Economics of Parallel System Design in Commercial-Scale Solar Plants

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Overview

The solar photovoltaic (PV) industry has enjoyed spectacular growth for the last decade. This has been due, in large part, to dramatic reductions in the installed cost of solar systems. Several factors have driven cost reductions: improved manufacturing efficiency, scale economies in purchasing, and improved installation labor efficiency.

However, despite the significant improvement in solar PV economics, further cost reductions are required to achieve grid parity. According to McKinsey's report on the economics of solar power[1], installed system costs need to be under $4/watt to reach grid parity in California, and under $3/watt for grid parity in Texas. To reach these goals, system designers are increasingly looking at system design innovations for cost reductions.

There is some precedent for this. Solyndra is one example: by redesigning their module (structural frame with smaller racking components, cylindrical PV cells for reduced wind load, and passive 'tracking' and rooftop sunlight reflection), they reduce the amount of labor, racking, and wiring required to assemble a commercial rooftop PV system. In this paper, we will describe another approach to design for cost reduction: the use of parallel system wiring rather than series.

This paper will outline the cost-reducing nature of a parallel system architecture, starting with an overview of series and parallel wiring schemes. We will then look at a reference system design, including a detailed electrical bill of materials. Finally, we will compare the difference in hardware and labor requirements, and therefore system costs, between the two architectures.

Series Architecture: The Current State of Design

Recall the basic difference between series and parallel circuits: when current sources (*e.g.*, PV modules) are wired in series, their voltages add; when wired in parallel, the currents add.

Series circuits are the dominant design choice in most PV systems today. Why? Because most PV modules deliver power at voltages that range from 25-35 volts (the maximum power voltage, Vmp,

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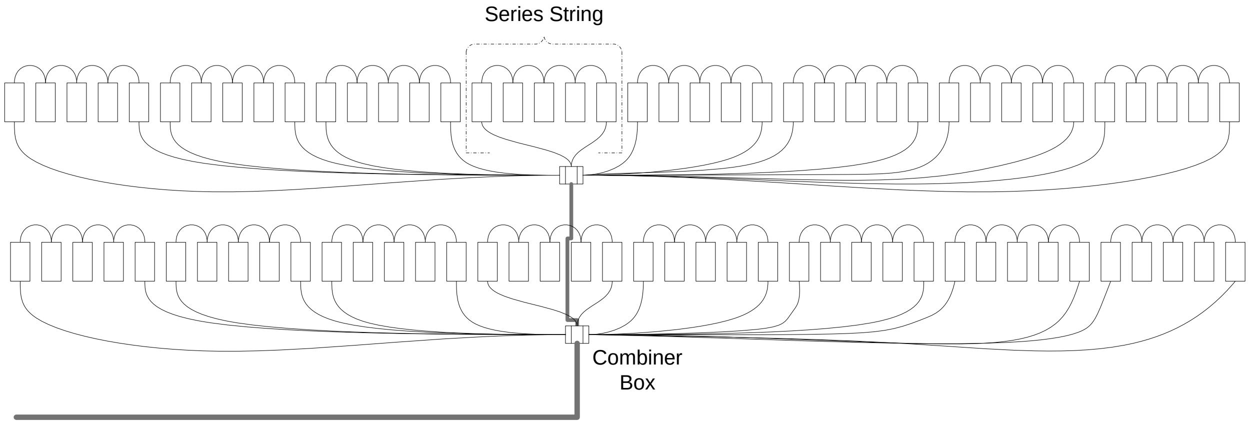
[1] "The Economics of Solar Power" by Peter Lorenz, Dickon Pinner, and Thomas Seitz, published in *The McKinsey Quarterly*, June 2008

for most crystalline silicon modules) to 50-100 volts (the Vmp for most thin-film modules). Most inverters, on the other hand, require inbound voltages between 240-480 volts. Thus, designers must wire modules in series so that the voltages add to a high enough level for the inverter. Most crystalline modules are wired in series, eight to 12 at a time. Most thin-film modules are series-wired in groups of five or six. These groups of solar modules, wired in series, are known as "strings."

Note also that the upward limit of a string size is determined by the open circuit voltage (Voc) of the PV modules. This value must also fall within the range of the inverter – and with any inverter designed to be used in NEC-regulated applications, the upper voltage limit is 600 volts. So for these inverters, the sum of the string's Voc must be under 600 volts.

Finally, all the strings are wired into a combiner box, which creates a parallel connection among them; this sums the current while maintaining the same voltage.

Image 1: Illustrative schematic of series wiring (represents 6.0kW of First Solar modules):



Note that the 80 modules are wired in series, which requires 16 five-module strings.

Parallel Architecture: A New Alternative

As implied in the discussion above, parallel system design is typically not an option because the voltage of the PV module is too low for the inverter to handle. Parallel system design requires a new component to boost the voltage from the levels delivered by the modules (anywhere from 18 volts to 100 volts) to the voltages required by the inverter. One such product is the vBoost, sold by eIQ Energy, Inc.[2] Because each vBoost unit's voltage output matches the inverter's ideal input voltage, the units can be wired in parallel, directly to the inverter.

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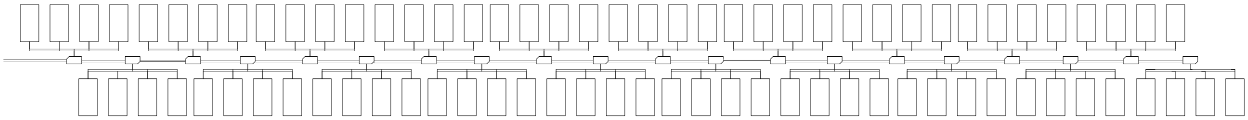
[2] eIQ Energy is based in San Jose, CA. More information can be found at www.eiqenergy.com.

With a parallel connection, the current adds, rather than the voltage. In other words, each cable can be used to its full current-carrying capacity. Therefore, more modules can be connected on a single cable run, which reduces system cost by reducing wiring and combiner box content. Some specific examples of these cost savings will be outlined below.

Image 2: Illustrative schematic of parallel wiring (represents 6.0kW of First Solar modules):



Note that the 80 modules are shown on a single parallel cable run

Bill of Materials Overview

The major cost drivers of a solar electrical system are wire (#10 AWG wire is most common), combiner boxes (fused boxes that combine multiple feeds into a single cable), and installation labor. In addition, a key system component for costing is a "string."

Strings: As mentioned earlier, a string is a self-contained electrical unit comprised of PV modules and their associated cabling. Thus, a string does not represent a single item on the bill of materials (and does not directly incur cost), but is a critical design factor in the overall system layout. String layout determines the quantity and cost of wire, combiner boxes, and installation labor in a system.

Wire: Wire is a factor in several system components. First is the string cabling, which is directly connected to the solar modules, and connects them to the backbone of the system (typically the combiner box). These are typically #12 or #10 AWG copper wires. Thicker cables (#4, #0, or larger) are then used for the "home run" cables, bringing the power from the combiner boxes back to the inverters, completing the circuit.

Combiner boxes: Combiner boxes simply take in multiple pairs of leads, typically between eight and 36, and combine them into a single pair. The number of combiner boxes in a system is a function of the number of strings in the system, as the leads of each string must be secured into a combiner box.

Labor: Electrical installation labor is a large component of the overall system cost. For our purposes, we will classify labor into two categories: simple electrical connections that can be done by hand, and more complex ones that require tools. Most connections at the PV module are MC3 or MC4 connectors. These do not require tools, so the labor content is small. However, connecting cables into combiner boxes is much more time-intensive: an installer must strip the wire and physically secure it into the combiner, usually with fastening hardware. Therefore, for the purposes of estimating labor, we will focus only on the labor associated with terminating the strings in the combiner boxes.

String Size and Count in a Series PV System

As mentioned earlier, series systems are designed to add the PV module voltages up to a level the inverter can accept. PV voltage is defined by its voltage at maximum power (Vmp), and its highest possible voltage when connected to an open circuit (Voc).

Table 1: Illustrative PV Characteristics

Module	Max Power Voltage (Vmp)	Open Circuit Voltage (Voc)
Evergreen Solar 205W	18.2	22.7
Sharp 175W	35.4	44.4
First Solar 75W	68.2	89.6
Signet 360W	146.4	187.6

In a series circuit, both of these voltage values are summed. In other words, a series string with N modules would, under normal operating conditions, deliver a voltage of N x Vmp, and could deliver a maximum voltage of N x Voc. This is relevant because both ends of the voltage output range must fit within the input voltage range of the inverter. As stated earlier, most standard inverters require inbound voltage to be between 300V and 600V. These parameters determine the minimum and maximum string lengths for each PV module[3].

Table 2: Illustrative PV characteristics and resulting series string length range

Module	Max Power Voltage (Vmp)	Open Circuit Voltage (Voc)	Minimum string length	Maximum string length
Evergreen Solar 205W	18.2	22.7	17 modules	26 modules
Sharp 175W	35.4	44.4	9 modules	13 modules
First Solar 75W	68.2	89.6	5 modules	6 modules
Signet 360W	146.4	187.6	3 modules	3 modules

Note: minimum and maximum string lengths calculated based on voltage range of 300V to 600V

Bill of Materials and Costs in a Series PV System

We will now analyze a reference design, to calculate the specific system components. Our reference design will assume a 1 megawatt system size, using a standard inverter (300V-600V input voltage), and First Solar 75W modules. (The calculations will be broken out, so readers can re-calculate the costs using different assumptions.)

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[3] Note that the PV module voltages will drop as temperatures rise, usually by -0.25 percent to -0.50 percent per degree Celsius. This adds complexity and challenges to string sizing in series designs. For the purposes of this exercise, however, we will ignore that issue.

Table 3: Reference Design Overview

System Attribute	Value
System size (watt-peak, DC)	1,000,000
PV module used	First Solar FS-275
Inverter used	PV Powered PVP-260kW
Wire used	#10 AWG

As shown in Table 1 above, First Solar modules in a series configuration can only be connected in strings of five or six. We will assume a string length of five, as this is a more common array design in practice. For a 1 megawatt (DC nameplate power rating) system, the plant will require 13,334 modules of 75W each. At five modules per string, the system will contain 2,667 strings.

With the string count defined, we can now determine the wire, combiner box, and labor content of a series system. Each string will require cabling from the PV modules back to the combiner box. In commercial installations, the average distance from series PV string to combiner box is 150 feet, so we can estimate the wire content based on the number of strings: 2,667 strings x 2 wires per string x 150 feet per wire run = 800,000 feet of wire. The 2,667 strings will also require combiner boxes: using 24-pole combiner boxes (again, a common configuration in practice), the system would require 112 combiner boxes (2,667 strings / 24 strings per combiner = 111.1 combiner boxes).

Finally, we have labor. As above, we will focus on the labor associated with terminating the strings in the combiner boxes – and here a conservative estimate is eight person-hours to mount and fully install a 24-pole combiner box (including setting and fusing the string terminations). Therefore, there are 896 person-hours of electrical labor embedded in this system, not counting the hand connections.

The cost of these components can show us the cost of the electrical balance of system. We will assume $0.30/foot[4] for the wire, based on #10 gauge copper wire, $1,000 for each combiner box, and $65/hour[5] for electrical installation labor. Given these assumptions, the total electrical system cost (not counting the PV modules or inverter, but everything in between) is $432,640, or $0.433/watt-peak.

String count in a Parallel PV System

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[4] Note that all prices are subject to change. Wire prices are particularly volatile, given their dependence on copper, an actively-traded commodity. At this writing, quotes for #10 AWG wire range from $0.26/foot to $0.34/foot for 1MW-sized quantities.

[5] We are assuming a US installation, at union wages. The series electrical balance-of-system installation requires skilled electrical labor.

We will now look at the same reference system design (1 megawatt, First Solar 75W modules, standard inverter), but assume a parallel system design. First, we need to determine the string count (or "cable run" count) of the system. This is where parallel architecture makes a huge difference.

In parallel systems, the number of PV modules on a single cable run is no longer determined by the voltage of the modules and the voltage of the inverter, as in the example above, but instead by the ampacity of the wire used. Each wire has different characteristics, and other factors such as temperature come into play, but #10 AWG copper wire can typically carry 30 amps[6] in standard conditions.

Returning to our reference design, each First Solar module delivers 75 watts of power, at 68.2 volts under maximum power. The voltage is then boosted – we will assume to 300V. (Most off-the-shelf inverters, with voltage ranges of 300V to 600V, are most efficient at lower inbound voltages[7].) At 300V, the current contribution of each First Solar module is only 0.25 amps. (75W / 300V = 0.25A.) Thus, a #10-gauge wire with a 30-amp limit can handle up to 120 modules per cable run. (Note that we call these "cable runs" rather than "strings" because the voltage does not add as it does in a series system. However, this is essentially a semantic difference.) With 13,334 modules, and 120 modules per cable run, the Parallel system contains only 112 cable runs. (13,334 / 120 = 111.1.) **Note that this represents a 24x improvement in string count over a series system design.**

Bill of Materials and Costs in a Parallel System

With the cable configuration of the Parallel system in place, we can add up the required components.

Starting with wire content, the system no longer has the thousands of strings that require home runs back to the combiner boxes. Instead, there are 112 parallel cable runs, each leading to a combiner box. Assuming 100 feet as the average distance from the end of the PV to combiner box[8], this system will only require 22,400 feet of #10 AWG wire.

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[6] The 30A limit for #10 AWG wire includes de-rating for operating temperature of 46-50°C, and de-rating for full-time use.

[7] See a list of CEC efficiencies at the following website: http://gosolarcalifornia.org/equipment/inverter_tests/summaries/

[8] The distance from parallel PV to combiner is smaller than in series (100 feet versus 150 feet) for two reasons. First, only one end of the PV array is wired back to the combiner box. Thus, the designer can run cable from the closer side (whereas in a series design, both ends of the string have to be run home. This can be seen in the illustrations above. Second, the fact that the strings are dramatically longer means that the designer can ensure

The combiner box count is also far lower in a parallel system. Only five 24-pole combiner boxes are needed for the 112-cable system. This also reduces labor requirements. Again assuming eight person-hours of installation time per combiner box, only 40 hours of combiner box installation labor are needed.

The total cost of a parallel system is thus far lower than the cost for a series system. With the same global cost assumptions ($0.30/ft for #10 AWG, $1,000 for a 24-pole combiner box, and $65/hr for electrical installation labor) the total cost of the solution (omitting the cost of the distributed electronics) is only $15,320, or $0.015/watt-peak (Wp).

Table 4: Cost Comparison Summary

		Series system		Parallel system	
Component	**Price**	**Quantity**	**Cost**	**Quantity**	**Cost**
Wire	**$0.30/ft**	800,000	$240,000	22,400	$6,720
Combiner box	**$1,000/unit**	112	$134,400	5	$6,000
Labor hours (total)	**$65/hr**	896	$58,240	40	$2,600
Total			**$432,640**		**$15,320**

Thus, we can see that a parallel system design yields a bill of materials cost savings, driven by wire, combiner box, and labor reduction, of $417,320. On a dollar/watt basis, this is a savings of $0.42/Wp (given the reference system size of 1MW).

Conclusion

We have shown the economic savings from a parallel system design, primarily driven by longer cable runs, which require fewer combiner boxes and less wire. We will now conclude with a few final comments.

First, note that the cost savings cited above are largely scale-independent. As systems scale, the electrical bill of materials (wire content, combiner box requirement) will largely scale with the number of PV modules. Therefore, while the above calculations were done on a 1MW reference design, they would apply proportionally to any commercial and utility-scale systems, from 30kW to multiple megawatts[9].

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that the parallel cable runs begin closer to the combiner box. This line sizing dynamic will be described in greater detail in future white papers.

[9] At small system sizes, the economic benefit of the string count reduction begins to break down. A large reduction in string count (here we saw a 24x improvement) is wasted on a system that begins with only two or three strings

The savings outlined also do not require any cost reduction from the inverter. Identical models were specified for each example, and the cost savings are comprised entirely of wire and combiner boxes.

Finally, we should keep in mind that a parallel architecture brings a host of other benefits in addition to cost savings. Since each current source in a parallel architecture runs directly into the inverter, it is **completely independent** from its neighbors. As a result, the system requires no balancing, and is more robust during failures or other adverse conditions. PV modules can be added or removed, without any modification to the other modules or the inverter. Different PV types can be combined on a single cable run, and fed into a single inverter. Also, a parallel system such as that enabled by the vBoost will improve inverter performance, primarily because the voltage sent to the inverter is carefully controlled at the inverter's peak efficiency point, which leads to less heat generation in the inverter.

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in series. In fact, many series-wired residential systems do not require any combiner boxes at all, so there is no way to further reduce them.

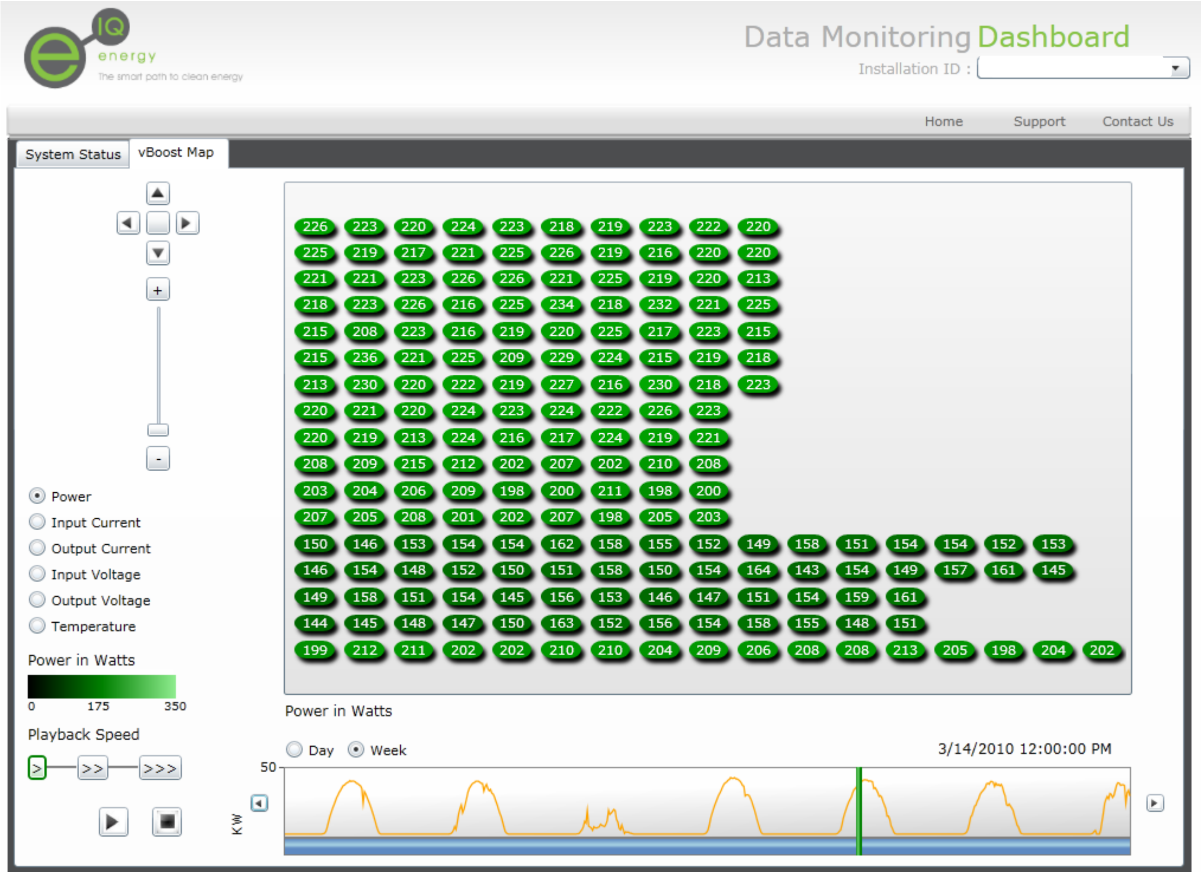
Appendix A:
eIQ Overview

Parallel economics and reduced system cost is only one of many benefits achieved through the vBoost from eIQ Energy. In this appendix, we will put the eIQ Energy value proposition (and cost) in context for the reader.

Value Proposition

There are multiple factors that drive value for eIQ Energy's customers. These include:

- **Reduced electrical bill of materials** – The above paper has outlined the cost savings from parallel architecture, from the PV to the first combiner box. eIQ's parallel system also improves the system cost from the combiner boxes in to the inverter. There is less cabling required, and dramatically less conduit required.
- **Increased energy harvest** – Depending on the system size and type, the increase in harvest can range from 5 percent to over 30 percent.
- **Improved monitoring** – The eIQ Energy system includes continuous data on how each vBoost module is performing. This enables enhanced analytics, more accurate performance modeling, and more efficient operations & maintenance. See below for a screenshot of the vBoost monitoring system:



● Power
○ Input Current
○ Output Current
○ Input Voltage
○ Output Voltage
○ Temperature

226	223	220	224	223	218	219	223	222	220							
225	219	217	221	225	226	219	216	220	220							
221	221	223	226	226	221	225	219	220	213							
218	223	226	216	225	234	218	232	221	225							
215	208	223	216	219	220	225	217	223	215							
215	236	221	225	209	229	224	215	219	218							
213	230	220	222	219	227	216	230	218	223							
220	221	220	224	223	224	222	226	223								
220	219	213	224	216	217	224	219	221								
208	209	215	212	202	207	202	210	208								
203	204	206	209	198	200	211	198	200								
207	205	208	201	202	207	198	205	203								
150	146	153	154	154	162	158	155	152	149	158	151	154	154	152	153	
146	154	148	152	150	151	158	150	154	164	143	154	149	157	161	145	
149	158	151	154	145	156	153	146	147	151	154	159	161				
144	145	148	147	150	163	152	156	154	158	155	148	151				
199	212	211	202	202	210	210	204	209	206	208	208	213	205	198	204	202

Power in Watts

○ Day ● Week

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- **Design flexibility** – With a parallel architecture, designers no longer have to balance strings, and modules can be mounted on multiple facings and angles of inclination, all feeding into the same inverter.
- **Faster installation** – The installation of the vBoost system can be performed in significantly less time than a series system. Most field connections are hand-done and require less coordination, and the system overall requires far fewer combiner boxes and less conduit. This enables installers to turn jobs around faster, which reduces their direct costs and improves throughput.
- **Safety** – The vBoost modules are not energized until the inverter is connected and turned on – and they can be turned off remotely, either online or by a switch at the inverter. This makes the installation safer for the installers, and provides a simple way to disconnect the system in an emergency such as a fire.

Product Configuration

An important factor in the economics of eIQ Energy is that the vBoost can be connected to more than one PV module, as long as the power, voltage, and current limits are maintained. Current vBoost units are rated at 250W and 350W. So one could feed four (4) 75W First Solar modules connected in parallel to a vBoost | 350, two (2) 175W Sharp modules connected in series to a vBoost | 350, or one (1) 220W Suntech module connected to a vBoost | 250[10].

This attribute means that low-power modules are not a problem for the vBoost, as they can simply be connected as a group into a single vBoost.

Cost

The vBoost costs depend on the system size and PV configuration, but the MSRP of the system is typically between $0.30 and $0.40 per watt.

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[10] These are just illustrative examples. The vBoost works with virtually any PV module.

Appendix B:
Line Loss (I^2R) Calculations

A common concern raised with parallel architecture is that the line losses are larger, since the current on the wire is greater. While this is true, we will here show that the size of this loss is an order of magnitude smaller than the cost savings enabled by the parallel architecture[11].

Parallel Circuit I^2R Losses

In the system described above, the parallel bus is approximately 240' long (120x First Solar FS-275 modules, each 2 feet wide), and drives 30 amps of current. For the sake of illustration, we will simplify the parallel bus to four[12] sections: each section 60 feet long, and contributing a single 7.5A source of current. We are also assuming #10 AWG wire, with standard operating temperatures (and a resulting resistivity value of 0.0999 ohms per 100 feet).

The calculations are shown below. Note that the losses get larger as the current builds up in the later sections (consistent with what one would expect with higher current). The overall power loss is 100.6 watts, which represents 1.12 percent of the 9,000W on the string.

	1st section	**2nd section**	**3rd section**	**4th section**	**Total**
Power (W)	2,250	4,500	6,750	9,000	9,000
Voltage (V)	**300**	**300**	**300**	**300**	
Current (A)	7.5	15.0	22.5	30.0	
Equivalent load resistance (ohms) (V^2/W)	40	20	13.3	10	
Wire size	**10**	**10**	**10**	**10**	
Wire resistivity (Ohms/100ft)	0.0999	0.0999	0.0999	0.0999	
Wire length	**60**	**60**	**60**	**60**	
Resistivity of wire (ohms)	0.060	0.060	0.060	0.060	
Total resistance	40.06	20.06	13.39	10.06	
Effective current	7.49	14.96	22.40	29.82	
Loss	**-0.15%**	**-0.30%**	**-0.45%**	**-0.60%**	
Loss (W)	-3.4	-13.4	-30.2	-53.6	-100.6
					-1.12%

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[11] Note that the calculations here are for the losses from the PV modules to the first combiner box. The line loss calculations from the combiner back to the inverter can also be calculated, but will not be significantly different.

[12] The use of four sections is relatively arbitrary. This same analysis could be done with any number of sections, from treating the cable as a single run, to breaking it up into 120 sections (one for each module). We chose four because it is small enough to be analytically clear, but provides enough granularity to illustrate the stacking current.

Series Circuit I^2R Losses

This compares with series string losses of 0.27 percent. Again, the calculations are shown below. Recall that the string consists of five FS-275 modules, wired in series. We are also assuming an average string length of 150 feet – this is because the shorter strings means that there are more strings, which therefore have a longer distance to travel before they hit a combiner box. Note that in this case, since each string is independent, the percentage loss calculations of a single string also apply to an entire series array.

	Series string
Power (W)	1650
Voltage (V)	**300**
Current (A)	5.5
Equivalent load resistance (ohms) (V^2/W)	54.5
Wire size	**10**
Wire resistivity (Ohms/100ft)	0.0999
Wire length	150
Resistivity of wire (ohms)	0.150
Total resistance	54.70
Effective current	5.48
Loss	**-0.27%**

Therefore, the total difference in line losses with parallel design is 0.84 percent (1.12 percent - 0.27 percent). In order to put a total dollar value on this production, we have to calculate the 20-year performance of this system.

NPV of Production Loss

Recall that the system size is 1,000,000W. We will assume a performance ratio (essentially a de-rating of the nameplate capacity for system efficiency) of 85 percent, production of 1,600 watt-hours per watt-peak, and an electricity market value of $0.15/kWh. For future performance, we will assume a discount rate of 10 percent, and an annual rate increase of 2 percent. Given all of these assumptions, the system production values are below:

Metric	Value
Annual kWh	1,360,000
Year 1 value of production	$204,000
Annual production loss	-0.84%
Year 1 value of loss	-$1,722
Total loss value (20-year, discounted)	-$18,833
Loss value $/Wp	-$0.019

Therefore, the total net present value of the higher I^2R losses is $18,833. This compares with installed savings of $417,320. The installed cost savings are over 22 times larger than the total value of the production loss.

Note that the IR losses could be reduced by going to a thicker gauge of wire for the close-in sections. While this is common in practice, we are ignoring it for the purposes of maintaining a consistent side-by-side comparison. This type of analysis will be the focus of future papers.

Appendix C:
Excluded components from analysis

The design & engineering of a solar plant can be infinitely complex. The paper here has explicitly focused on the electrical system installed cost. We have also focused only on first-order cost drivers. While we could add dozens of other factors to increase the accuracy of the analysis, it would obscure the major point. Here, we want to acknowledge the other second-order effects that we have excluded, and outline the reason behind excluding them.

Field installation labor: The labor to install the vBoost is small. The units are mounted using two screws, and all electrical connections are MC3/MC4 connectors (done by hand). This is also not purely incremental labor: it replaces the field connections of strings, which also use MC3/MC4 connectors. Plus, the added simplicity of the parallel wiring (no strings to plan around) will offset much of the additional hardware mounting costs. These calculations will be the focus of future white papers, but the current field testing shows the total parallel install time to be on par with a series installation.

Conduit: Because parallel wiring reduces the number of strings and combiner boxes, this also leads to a significant reduction in the conduit required for the system. Conduit requires significant labor, special hardware, and also results in the de-rating of the cabling (requiring the designer to upgrade the cable used). This is a strong benefit of parallel design, but is omitted here for simplicity.

Design time: Designing a parallel system is much simpler than designing a series system. The designer no longer must balance strings; instead they just lay out all of the units, and connect them together until they reach the current limit of the wire. However, since this simplification is difficult to quantify and monetize, we are omitting it from this analysis.