Manhattan 2 Building & Land Integrated Rollable Solar PV Research Initiative

By Glenn Weinreb, CTO, Manhattan 2, Printed Dec 2, 2020

Chapter 1) Summary

We intend to develop electrical and mechanical standards, and construct early prototypes, for a roll-format of photovoltaic (PV) material with embedded electronics. We support all PV technologies, including silicon. This is conceptually similar to the standard 35mm film canister system, yet larger (e.g. 6 ft diameter, 6 x 150 ft when flat).

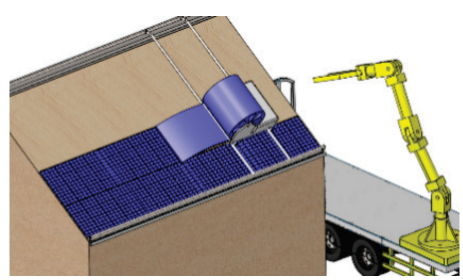
Flexible solar PV products based on low cost silicon with 21.7% efficiency currently exist (e.g. 5 x 2 ft, 0.1" thick). We propose a similar, but much larger rollable material that may be cut into custom shapes to fit a wide variety of building surfaces, such roof and wall surfaces of both commercial and residential buildings (e.g. direct to plywood). We will design cuttable PV materials, perform 30-year life simulations, and investigate the development of specialized installation machines.

The new material includes embedded PCBs consisting of arrays of 300W MPPT 50V DC-to-DC converters networked via CANbus. Strings of eight generate 400VDC and multiple strings combine in parallel.

Building Integrated Photovoltaics (BiPV)

Architectural drawings are sent to factory who makes custom solar pieces, as needed, to attach directly to plywood and other surfaces. Pictured below, left to right: (1) existing product Renogy 160W flexible silicon solar panel (2) illustration of solar direct to residential roof *and* wall surfaces, and (3) illustration of potential machine that installs solar.



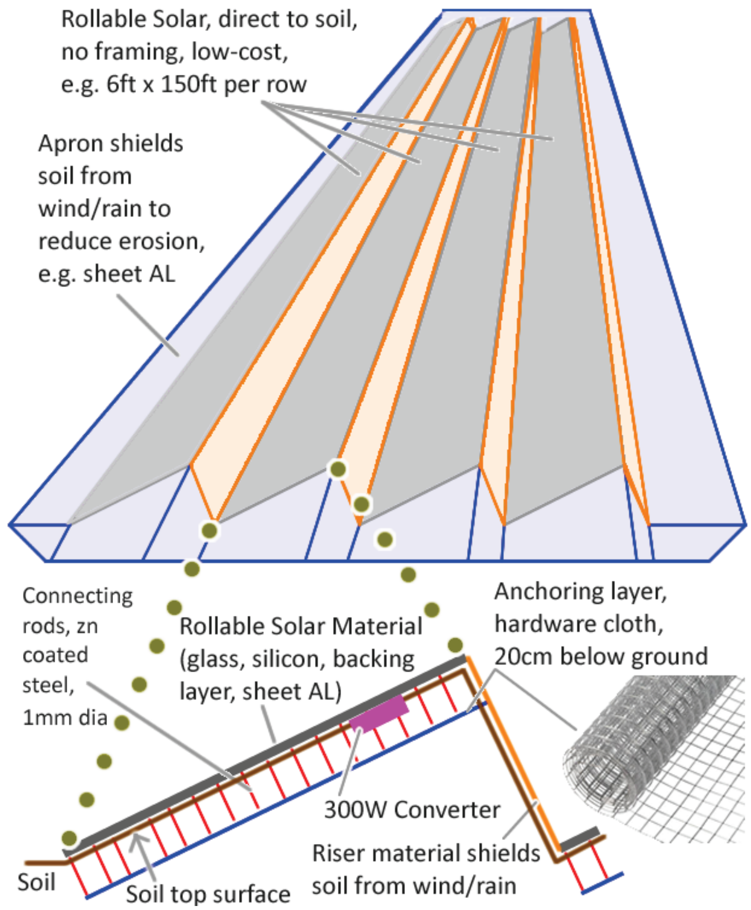


If one has a plywood roof that is 40ft wide x 30ft high, for example, they might place five overlapping strips of material directly onto plywood, where each strip is 40ft wide x ~6ft high. Horizontal metal rails might secure at overlap positions, and vertical batons might resist movement during high winds. Researchers simulate 30 years of UV, thermal cycling, etc.

Project emphasis: make building-integrated PV (BiPV) a reality, reduce cost of PV on buildings and land, develop built-in field testing that predicts long term component failure, and develop standards that help others create machines that fabricate and install. This project could potentially become the basis for how the world coats buildings and land with solar, and therefore could have a global impact on decarbonization.

Land Integrated Photovoltaics (LiPV)

We will explore adapting solar PV material for placement directly onto soil, on land, to create a cost-reduced method of high-volume installation via automated machinery. A road roller prepares rows of soil at ~30° angle pointed toward sun; while a different machine unrolls material onto soil. One might have an anchoring layer (e.g. steel mesh on 1cm matrix) ~1 ft below ground that connects to top solar layer via steel wire. Researchers simulate 30yrs of wind, rain, erosion, etc.



Farmers Plant Beds of Corn *and* Solar

Automated machinery plants beds of solar, co-located with agricultural farming activity. Apron surrounds bed to control soil erosion from wind and rain. Water flows to catch basins at solar edge, into pipe, and toward agricultural crops. Top surface is factory washed to remove harmful chemicals. Motion detector powers-off when PV area is entered. Researchers model effects of climate, geology, wind, rainfall, snow, etc. Researchers also explore specialized farm tractor attachments that transport, install, and clean rollable solar material. Rollable solar on agricultural farms differs from rollable solar on solar farms in the following ways: (1) water is optionally collected and directed toward crops, (2) more automated safety due to colocation of crop workers, (3) utilization of existing farm equipment to help install and maintain solar.

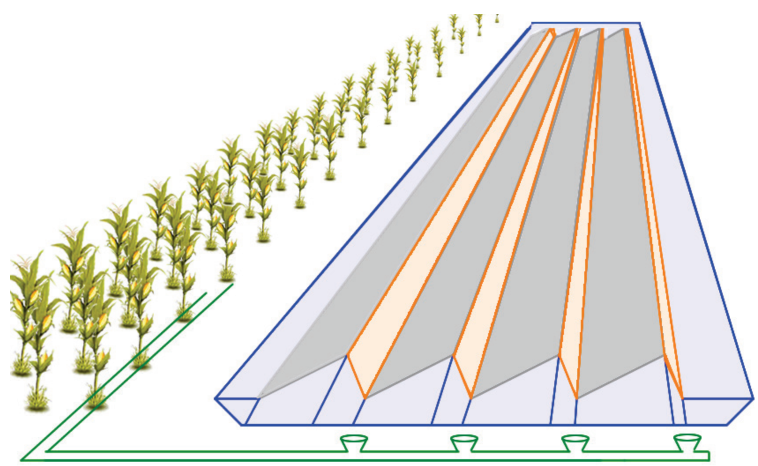
Agricultural Farms are Natural Locations for Mechanized Deployment of Solar on Land

The best way to massively increase solar PV deployment on agricultural farms is *not* to mount solar above crops, since that is expensive for a variety of reasons. If one wants to encourage agricultural farmers to deploy solar on a massive scale, they should focus on increasing farm profit via several methods: (1) decrease costs via automation, (2) tightly pack solar to reduce land consumption, (3) redistribute rain water from solar bed to plants.

Farmers should consider planting solar the same way they plant corn, with large sophisticated machines. It is our intent to design the solar PV material that is handled by those machines and to introduce it to manufacturers of (farm) equipment that fabricate, install and maintain massive deployments of low-cost solar on land.

Farmers are a natural fit to plant solar for several reasons: they have land, they are accustomed to working with machines, their machines could probably be adapted to work with solar via attachments, they know how to maintain complex systems, and they know how to run a business.

Decarbonizing America without Nuclear Power



One possible decarbonization pathway (i.e. method to stop emitting CO_2) is to cover 25% of Nevada with solar PV (74K km^2 land, 37K km^2 PV) and then make hydrogen gas (H_2) with the electricity. H_2 could be transported throughout America to power vehicles, heat homes, and generate more electricity. In this scenario, the electricity generated is ~3 times more than what America currently generates since this system would be replacing energy we currently obtain from burning natural gas, coal, oil, and gasoline (i.e. we are decarbonizing, 10.4K vs 3.8K TWhr/yr). The solar parts and labor might cost ~$3.7T ($150B/yr over 25yrs, $0.50/Watt, 7.4TW capacity); however, this does not include the following costs: electrolysis to convert electricity to H_2, transportation/storage of H_2, maintenance of solar, and land ownership. This solves the following *problems*: USA decarbonization (fully stop emitting CO_2), energy storage (H_2 is storage), limited rare earth metals for many EV batteries (cars run on H_2), significant electrical grid expansion (no longer needed), and disruption to communities from locally based wind/solar/nuclear. The disadvantage is cost -- consumers would see a significant increase in energy prices. Getting it done requires mechanized mass deployment of solar, which we intend to develop.

Can We Roll?

The following can all roll: Monocrystalline Silicon attached to flexible plastic (e.g. existing products Renogy Mono Silicon 50W rollable panel or Lensun Flexible Solar Panel), glass (e.g. Corning Willow Glass), and sheet metal (e.g. Chicago Metal Rolled Products, CMRP); all pictured below.



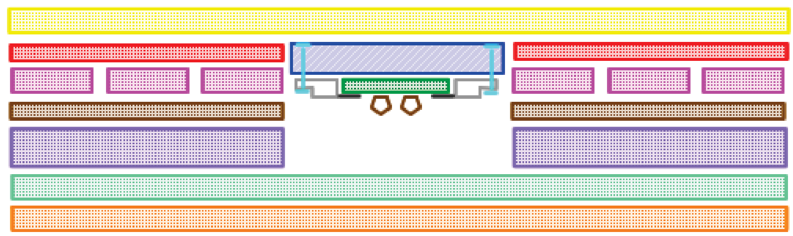
There are several forms of solar conversion material (e.g. silicon, thin film), each with their own mechanical constraints (e.g. maximum bend radius), conversion efficiency (e.g. 22% with Monocrystalline Silicon) and lifetime trajectory. Existing flexible silicon solar products are currently being mounted on curved surfaces; however, these can fail prematurely if silicon is heated or bent excessively, as discussed in this video. Subsequently, researchers must determine an acceptable minimum bend radius, and thermally conduct heat to top surface to reduce temperature (i.e. no thermal insulator between silicon and top glass layer), for each type of PV technology.

Bending silicon effects lifetime and therefore deserves further exploration. To help understand the effects of storing in a curved state, researchers store cells of different types, at different curvatures (different radius), at different temperatures, and periodically measure efficiency. It is our intent to publish a paper that accurately models the effect of bending during storage on lifetime and efficiency, for several PV technologies. A typical 22% efficient 6in silicon cell is 0.008in thick and easily deflects by 0.5in (1m radius) without breaking, with only 0.03LBs of force, for example (36in = (6^2 + 0.5^2) / (2 * 0.5)).

Roll-to-Roll Manufacturing Supports a Laminated System

Researchers design solar material that is capable of being mass produced in a factory using robotics and roll-to-roll manufacturing.

An example stack-up is illustrated below, not drawn to scale. The top layer (yellow) is tempered glass that protects the underlying silicon PV cells (violet). The PCB (green) is bounded to a gold-plated metal plate (blue), which conducts heat to the top surface. Plating with gold reduces PCB heating by the sun, as noted in this 1969 paper. Silicon PV is encapsulated in top (red) and bottom (brown) electrical insulation (e.g. EVA). Honeycomb core material (purple) fills space where the PCB does not. Thermal insulation (light green) protects underlying material from fire, and aluminum base material (orange) provides strength.



In this approach, we replace PV collection area with PCB heat sink to reduce long term silicon PV efficiency degradation due to additional silicon heating. If PCB is 15cm x 22cm and is positioned every 1m x 1.5m, for example, we would see a 2% energy loss due to reduced solar collection area (.15*.22/1.5). Researchers compare this with pushing PCB heat through electrical insulation and through silicon; which might affect silicon efficiency. Efficiency degradation in one cell limits the power harvested from neighboring cells; therefore, maintaining a cool temperature in 100% of the cells is important.

An example of a roll-to-roll assembly is shown here. These machines are not exactly what we need -- we show this to illustrate the concept of roll-to-roll lamination.

Costs & Benefits

The table below shows the cost and properties of materials for one design approach. We estimate one can bend a 1m wide x 1.5m long x 1.4cm thick piece of solar material along a 1m radius (90°) with only a few LBs of force (i.e. it bends easily).

Layer	Thickness (mm)	$/kg	Density kg/m³	Layer Weight (kg/m^2)	Layer Cost ($/m^2)	Bend Force 1m wide 90° arc (N)
Tempered glass	2.0	5	1200	2.4	$12.00	0.124
Silicon PV Wafer	0.5	0.00	2300	1.2	$0.00	0.887
SOLAR-IMB Back Sheet Laminate from AIT (Electrical Insulation)	2.0	0.72	1800	3.6	$2.59	0.071
Polypropalyne, 30% cellulose fiber, impact modified (Honeycomb Core)	8.0	0.58	1040	0.8	$0.48	0.004
Glass Fiber Woven Roving with Cloth Material Fabric (Fiberglass Cloth)	1.0	1.15	2600	2.6	$2.99	4.670
Aluminum 6061-T6; 6061-T651 (Sheet Metal)	0.5	2.00	2700	1.4	$2.70	0.556
TOTAL	14.0			11.9	$20.76	6.312

The above table does *not* include the following costs: silicon PV cells, roll-to-roll fabrication, and electronics. Silicon PV cells are approximately $15/m^2 as of June 2020 ($0.08/Watt for 22% Superior High Efficiency Mono-Si Cell, 194W/m^2 = 900W x 21.7%, 194W x $0.08 = $15/m^2). We estimate electronics parts and labor to be $0.17/W based on our initial design. And we estimate high volume material fabrication at $10/m^2. This works out to $79/m^2 or $0.40/Watt total. This does not include the following costs: installation, maintenance, and customer acquisition.

Item	Cost ($/m^2)	Cost/Watt
Silicon PV Cells	$15.62	$0.08
Solar Material Cost (w/o Silicon PV & Electronics)	$20.76	$0.11
Material Assembly Cost (estimate)	$10.00	$0.05
Electronics Cost, parts and assembly labor ($50/300W, estimate)	$32.55	$0.17
Total	$78.94	$0.40

EnergySage.com reports that the average residential project is 6kW in size with a $3/Watt parts and labor cost.

Our goal is to significantly reduce the cost of residential, commercial, agricultural farm and solar farm applications. Our approach differs in the following ways:

- In the case of buildings, we coat the entire roof, edge to edge, dramatically increasing energy output. We possibly cover walls as well, further increasing output. This is crucial when attempting to achieve zero net-energy use.
- If customer acquisition cost is constant and we increase kW output three-fold then customer acquisition cost-per-watt improves by a factor of three, for example. This is important, since current customer acquisition cost is high relative to solar parts cost. For example, we estimate our system parts cost to be $0.40/W; whereas average residential customer acquisition cost is $0.52/W.
- We do not have roof shingles or wall side clapboards under our material, which significantly reduces cost since installing shingles/clapboards is labor intensive.
- We intend to connect all electronics to the network via a standardized communication protocol that we propose, which will dramatically reduce maintenance costs since all interested parties will be able to interact with

hardware from different manufacturers using the same software, from virtually any location.

- We intended to measure component properties each night (e.g. MOSFET gate leakage current), which will enable us to estimate longevity significantly before failure. And, we will propose a standardized method for reporting component properties and longevity. Arming the market with lifetime data will influence buying decisions, push on suppliers to provide reasonable lifetimes, and therefore reduce costs.
- We do MPPT every 1.5m^2 and are therefore not vulnerable to the traditional problems associated with long strings, which are costly.

In summary, we reduce cost via multiple methods: (1) less manual labor since machines handle larger pieces, (2) no weatherproof cables and connectors under panels, (3) no shingle cost when direct to roof, (4) no side clapboard cost when direct to wall, (5) MPPT every 300W avoids long string vulnerabilities, (6) mechanical, electrical and communications standardization reduces cost via increased competition ("commoditization"), (7) free and open reference designs results in less R&D costs by manufacturers, (8) less mechanical framing cost due to rigidity from underlying material.

Heat

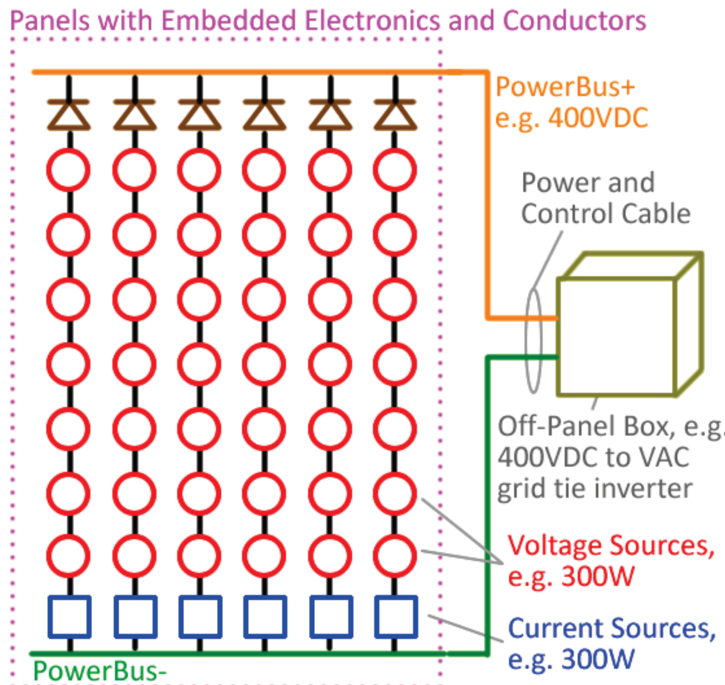
Sun radiates ~900W/m^2 and typical silicon PV efficiency is ~20%; therefore, ~80% is converted to heat within the silicon. This works out to 0.07W/cm^2 or 0.5W/in^2 (900*0.8 / (100*100)). Heat from electronic components is ~¼ as much as heat from sun light (e.g. 0.11W/in^2 = 6W/54in^2 PCB, 6W is loss from 98% efficient 300W DC-to-DC converter, ~6x9in PCB size). One might dissipate heat at 43°C/W/in^2 via convection at top surface, therefore, 0.5W/in^2 would increase Si temperature 21°C (e.g. 105°F (40°C) outdoor temperature, 142°F (61°C) Si temperature).

Buildings often have thermal insulation in their walls and roof; therefore, researchers must move heat to the top surface. Silicon degrades faster and is less efficient when warmer. Subsequently, we will consider transparent thermal grease or thermally conductive adhesive between Si PV and glass top layer, to better conduct heat upward. In traditional solar panels, Si wafers are embedded in EVA (it is both above and below Si). In our case, we need to rethink layers above Si and search for materials that are thermally conductive, transparent, stable in UV, and resist mechanical shock from hail stones.

Embedded Electronics

If one connects 1000 Volts of solar cells in series, for example, and electrical current degrades in one cell, for any reason, then current that flows through the entire string will be limited by what flows through the lowest performing cell. Subsequently, it is advantageous to maximize the power received from smaller regions, and then combine. Our strategy is to embed fault-tolerant electronics into the solar material that independently manages each ~1.5 square meters of solar material, via arrays of DC-to-DC converters that perform Maximum Power Point Tracking (MPPT) on each 1.5m^2 section of solar PV material.

Arrays of DC-to-DC Converters



We will network together an array of DC-to-DC converters where each converts 24...75V to ~50V. Eight electrically floating converters will produce ~400VDC via one string. Multiple strings will combine in parallel. Converter PCB's spaced every 1.5m^2 shed 4.5W with 98.5% efficiency, for example. Off-panel inverter converts 400VDC to grid-tie VAC. Master Controller PCB manages array elements and inverter. Each 300W element contains a buck and boost converter, where only one is on at a time. The #XMC4200 $3.30 processor provides CANbus communication and power conversion. PCB electrically floats via isolated CANbus transceiver (#ADM3050e, $2) and isolated 5VDC-to-5VDC power supply module (#PDSE1, $1.56). MOSFETs and Capacitors rated for 100V are low cost and low height (≤ 7mm).

More Wires Provides More Opportunities

A multi-wire cable connects 300W PCB's. This differs from traditional systems and provides several benefits: (1) ≥ 99.999% fast reliable CANbus communication for array management, (2) 48VDC external power enables built-in field tests with no PV power (e.g. measure gate leakage, Voc), (3) master reset opens switches, and (4) Ground Fault Protection (GFI).

Managing Component Degradation via Standardized Built-in Field Testing

Multiple voltages and currents are monitored on each 300W converter enabling one to measure Cin, Cout, L, MOSFET Ron, MOSFET Gate Leakage, and PV Voc. Researchers propose standard ways of reporting parameters to server. Real-time monitoring of degradation enables customers to scale to larger volumes *after* lifetime performance has be verified.

Managing a Lifetime of Faults

Let's assume 300W PCB's fail occasionally and cause total array output to decrease over time. Researchers determine acceptable level (e.g. 5% electrical system degradation over 25 years) and develop failure models that meets this level. To reduce failure rates we: (1) use ceramic instead of electrolytic, (2) avoid high temperatures with only 4.5W per 1.5m^2, (3) field test stressed components, (4) bypass MOSFET engages if 300W PCB fails, (5) three out of eight converters must fail to bring down one string, (6) fewer exposed cables and connectors, and (7) avoid traditional long string vulnerabilities with MPPT every 300W.

Fire Control

We reduce risk of fire via several methods: (1) manage 300W at a time vs larger (2) Master Reset signal causes all MOSFETs to open, (3) safety MOSFET disconnects PV, (4) multiple temperature sensors hardwired to Reset, (5) powering down external 48VDC power supply causes all MOSFETs to open, (6) current shunts look for PV+- current mismatch, (7) bottom layer of solar material is "last line of defense" thermal insulation layer. Researchers force multiple faults, measure temperatures, and design system that cannot heat plywood excessively.

Project Risks

There are multiple project risks, several of which are as follows: premature mechanical or electrical failure, deficient measurement accuracy, deficient fire control, deficient safety, lack of interest from standards body, and lack of interest from companies who design and manufacture machines that fabricate and install material.

Manhattan 2 Smart Building Interconnection Standards Development Initiative

Manhattan 2 (Ma2) intends to develop electrical, mechanical, and communications standards that define how devices interconnect within the building of the future. Devices include motors that control thermal covers over physical wall windows, motors that control curtains and blinds, fans in ducts, dampers in ducts, lights, occupancy sensors, washing machines, ovens, refrigerators, dish washers, HVAC systems, pumps that control 58°F ground source water, thermal storage water, valves on room water-filled radiators, etc.

This initiative involves developing a 2-wire communication standards between multiple devices that provides the following features: supports CANbus communication between ~$1 microprocessors, no damage upon accidental short to power wires, devices use little power when not in use (sleep), wiring supports tree topology (daisy chain not required), hot socket compatible (no damage when attach wires with power on), ≥ 99.999% reliable (not wireless), and transceivers consume ≤ ~10mW of power when signaling (as opposed to ~10x more utilized by RS-485 or 120Ω CANbus).

We are calling this new network "BuildingBus™", for lack of a better term, and there are two versions. *BuildingBus 48V* caters to lower power and lower voltage whereas *BuildingBus AC* caters to higher power and higher voltage. *BuildingBus 48V* routes 48VDC power to devices with ~200W/network; whereas *BuildingBus AC* routes 110/220VAC power with ~2,000W/network to devices. Fans, industrial lighting, and motors that move heavy windows require 110/220VAC; whereas many other devices are 48V capable. 110/220VAC cable is bulky and needs to conform to high voltage building codes (i.e. conduit more likely), whereas 48VDC cable is lighter and satisfies low voltage building requirements. For details, search for "BuildingBus Development Initiative" in file Active Window.

We make use of existing standards whenever possible, and propose new standards as needed.

Researchers do *not* necessarily design products to be manufactured and sold. Instead, they propose interconnection standards, and prototypes that demonstrate those standards. These are then provided to standards bodies (e.g. IEEE), which modify as desired, and establish plug-and-play standardization.

All materials produced by researchers are given away for free, to encourage utilization by standards bodies, to reduce CO_2 emissions. This includes mechanical drawings, electrical schematics and software source code.

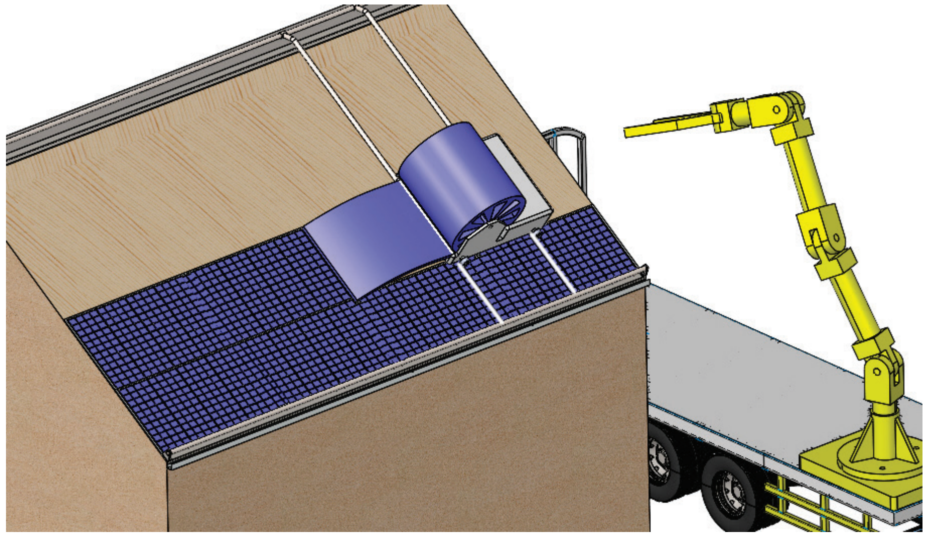
Ma2 is also developing standards that define how solar material attaches directly to building surfaces, such as plywood. The proposed solar material is ~1.5cm thick and contains embedded electronics that perform power conversion. This material can be applied to both roof and wall surfaces, edge-to-edge.

Prototypes develop by researchers use the same processor, and utilize common code. This helps researchers move quickly. Cost reduction is a later step, done by industry, after standards are finalized. The Xmc4200 processor, for example, supports almost all devices. A prototype that moves a window thermal cover, and a prototype of the DC-DC converter embedded in solar material, can both be implemented with this one processor, for example. It provides: 16x 12bit a/d channels, 2x 12bit d/a channels, analog comparators, 2 CANbus channels, counter/timers, 256KBFlash, and 40 KB Ram. All within one tiny package.

See Also:

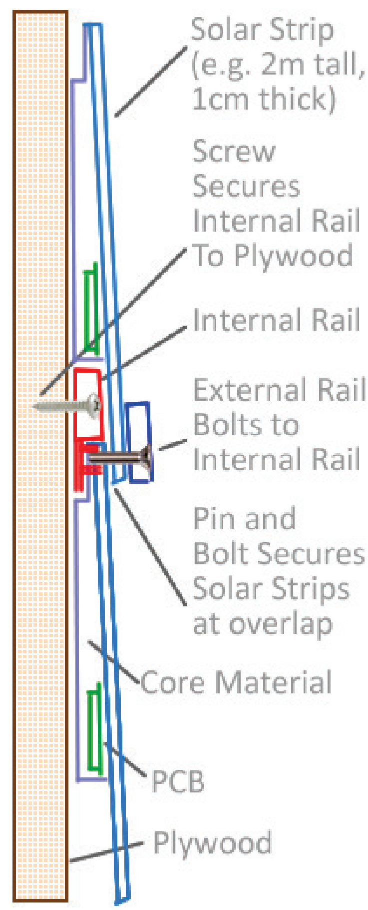
- Ma2 Smart Building Interconnection-Standards Development Initiative (Plan)
- Ma2 Active Window Development Initiative (Plan, Research Teams Yr1)
- Ma2 BiPV/LiPV Rollable Photovoltaic Research Initiative (Plan, Research Teams Yr1)
- Ma2 Fan and Damper Interconnection-Standards Development Initiative (Plan)

Chapter 2) Direct to Plywood, Residential Roof and Wall (Ap1)



Each application requires a unique standardized mechanical system to coordinate machines that manufacture, handle and install the material. Mechanical engineers start with a few, summarized below. We refer to these as "Applications" and give them a designation code (e.g. Ap1 is solar direct to plywood).

In the case of solar on buildings, architectural drawings are sent to a factory who makes custom solar pieces, as needed, to attach directly to plywood & other surfaces.



Currently, drywall is sold in 4x8ft sheets and is cut into custom shapes as needed for windows and doors. Architectural software provides a list of required shapes. We expect the same for large pieces of BiPV.

Researchers consider attaching rollable flexible material direct to plywood, and look at the various ways one might install and secure to a surface.

Material is shipped from factory in a canister, in a standardized mechanical format, similar to analog film. Notice how this standard enabled the industry of film manufacturers to produce something that is compatible with cameras made by different companies. Without this standard, neither industry would have existed.

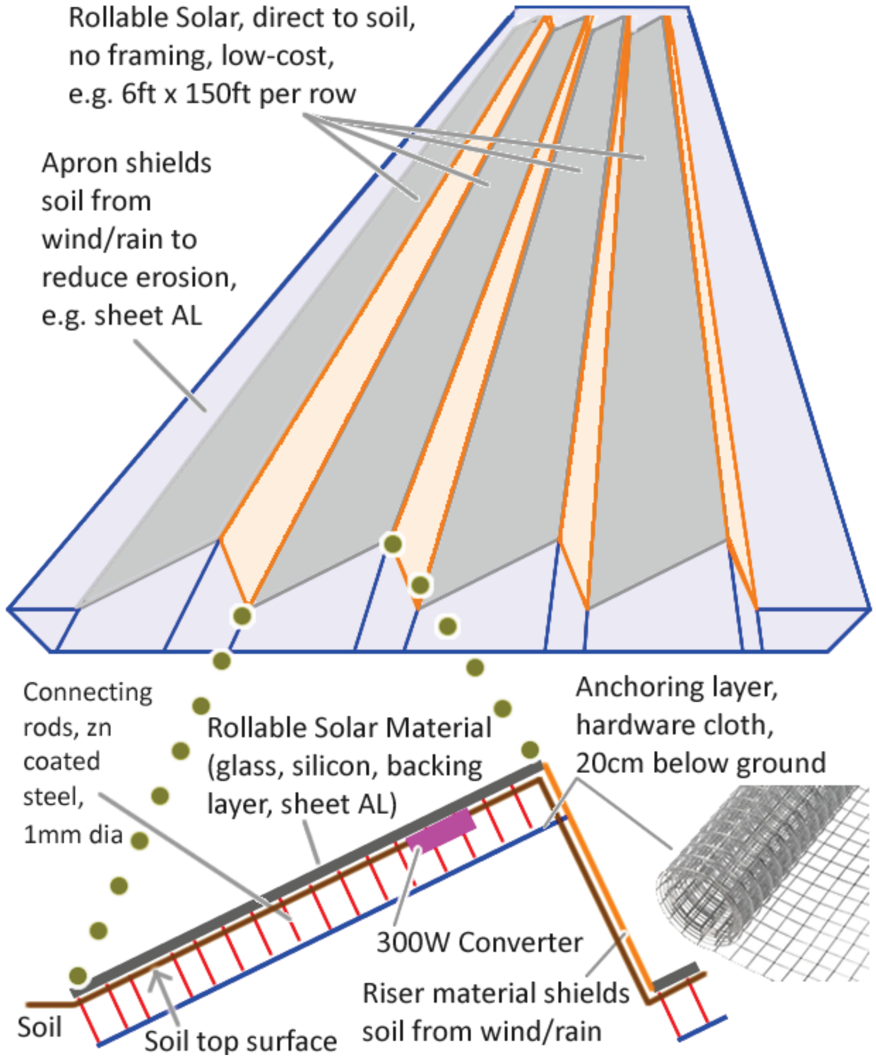
The illustration to the right, not drawn to scale, shows how one might attach overlapping strips of solar direct to plywood wall or roof. Each strip might be 2m (6ft) high, 2 to 10m wide, and 1 to 2cm thick. At the overlap position, an internal metal rail (red) affixes to plywood via screws, and an external metal rail (dark blue) binds to internal rail via bolts. The upper solar strip and lower solar strips overlap at this position and are sandwiched between the two rails. Perforations (holes) in solar material allow bolts and pins to penetrate and secure. Traditional roof shingles and side clapboards route water across overlapping joints, and we will do the same. For an exploded view of a possible overlapping solar joint, click here.

Cover Both Roof and Wall Surfaces, Edge-to-Edge

The Illustration to the right shows solar material on both roof *and* wall surfaces, *edge-to-edge*. We believe this will be the de facto standard in the future. Horizontal external rails (light gray) bolt to underlying horizontal internal rails. Vertical external batons (also light gray) affix to horizontal external rails, and help secure material. Glue is not used, since disassembly is required to replace and/or repair.

Initially, researchers focus on developing solar material to the extent that computer simulation shows it surviving many decades of wear-and-tear. After the material and its securing mechanism is better understood, they can think about machines that handle it.

Building Integrated PV (BiPV) has been theorized for many decades, yet does not exist. Why not? We believe the reason is a lack of mechanical and electrical standards that coordinate an industry of companies that manufacture, handle and install BiPV components. We consider it our job to develop working prototypes and propose standards, to the extent that standards bodies (e.g. IEEE) can build on top of our work.



"Land Integrated PV" (LiPV), refers to PV material placed directly onto soil, on land, without metal framing underneath. As of today, LiPV for the most part does not exist. Yet why not? Land could provide rigidity, and eliminate the cost of framing and foundations under the solar material. For a video that shows an existing LiPV product, click here. This existing product is not designed to deploy for long durations, yet demonstrates the concept of rollable LiPV.

In order for LiPV to work, long term, it needs to be stable in wind and resistant to soil erosion. Regions with large deserts might consider populating them with beds of low-cost solar that is installed with large automated machines.

Let's start with solar material that contains embedded electronics and assume it is 2 x 50 meters (6 x 150ft) when flat. It is transported in a 2 to 3m diameter roll, inside a shipping container or truck. It is 1cm thick and is flimsy to reduce cost. Now, let's place this onto land, at a 30° angle toward the sun. A side view of what this might look like is shown above. The solar material is gray (e.g. glass, silicon, plastic backing layer, sheet aluminum), vertical riser material is orange (e.g. 0.3mm thick metal), soil is brown, and a hardware cloth anchoring layer ~12in below ground is blue. A light blue apron surrounds the bed to control soil erosion due to rain and wind (e.g. 0.3mm thick metal). Wind that develops negative pressure pulls material upward; therefore, an underground anchoring layer (e.g. hardware cloth) is required.

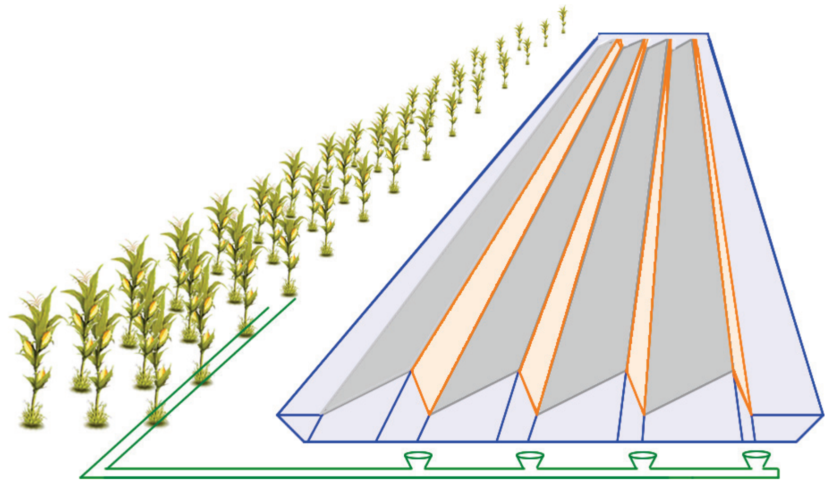
The soil under the material might be shaped and compacted with a specially adapted roller and the scraper, under computer control. The traditional versions of these machines are pictured below.

LiPV is ideally suited to regions where the ground is firm and does not change much due to wind/rain, wind is low, and rainfall is low. A desert with moving sand dunes (lower right) might get covered too easily. An area with much rainfall needs erosion control; which is feasible yet adds cost (i.e. water carries soil particles and moves them).

Shown at lower left is Arizona, which sees 25cm (10") of rain-per-year and has somewhat stable soil (does not move much in wind). In contrast, Saudi Arabian sand, pictured lower right, moves easily in wind.

Researchers simulate the effects of wind, rain, freezing water, soil erosion, UV, thermal cycling, and hail stones; and determine what it takes to make this work for various climates and soil, at reasonable cost.

To control erosion, rain water can either enter soil through holes in a trough or can travel along 50m length to a drainage basin that attaches to a pipe, which routes water away from solar material, as shown here.



Researchers might create a prototype using sheet metal, instead of solar material, place markings on material (e.g. 1" diameter black stickers), photograph it periodically, and look for movement (cameras and software can reconstruct surface accurately).

Agricultural farms use wheeled trusses to deploy water. One might have a similar system which cleans panels and removes debris from trough.

Reducing the Cost of Solar on Land

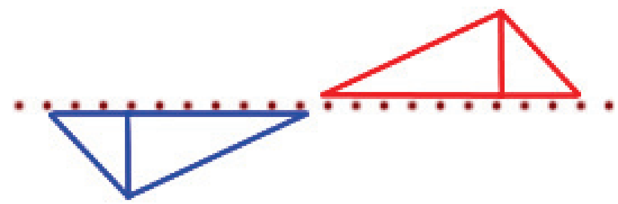
An example modern solar farm is Topaz Solar. This cost $4.80/Watt ($2.4B / 500MW). In theory, 8% of this could cover the cost of solar PV cells, layers of material in rollable solar, and electronic components embedded in rollable solar ($0.40/W, as discussed previously). 92% are "other" costs that we aim to tackle via: (1) standardization to the extent of commoditization & interoperability between multiple suppliers (drives down price), (2) reporting of component properties in a standardized manner (arms market with lifetime data), and (3) automated installation & maintenance machinery (reduces labor costs).

Prepare Your Desert For Solar

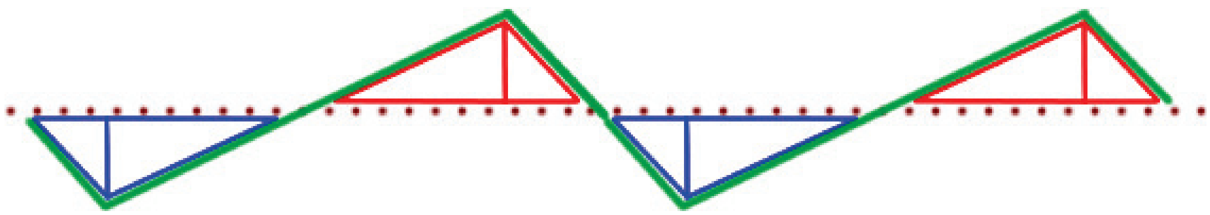
A bulldozer costs approximately $12K/month. If one dozes 6 hrs per day at a rate of 3mph, then one could cover 2.1M linear feet each month (6*23*5280*3) at a cost of $0.005 per-linear-ft ($12K/2.1M). A scraper cost $32K/month ($175/hour * 23 * 8) which works out to $0.015 per-linear-ft (3 times more than dozer). A road roller cost $9K/month ($50/hour * 23 * 8), which works out to $0.0037 per-linear-ft.

If one prepares the desert with two bulldozer passes, two scraper passes, and 2 roller passes, then total cost would be ~$0.06 per-linear-ft (0.015*2+0.015*2+$0.003*2). If machine width is 6ft and 50% of the prepared land is used for solar, then cost to flatten land prior to adding rows of solar works out to $0.18 per-square-meter of solar material ((($0.06*3)*2)*50%) or $0.0009/Watt ($0.18/200W). Each square meter is good for 200Watts of power.

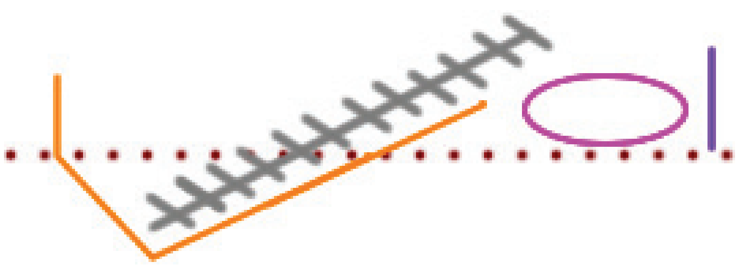
Moving a Triangle of Material

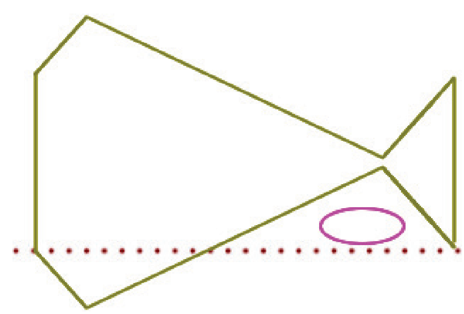


The next step might be to transfer a triangle of material from below (blue) the soil line to above the soil line (red), as shown to the right. The original soil line is show in brown. This would result in a new soil line, shown below in green.



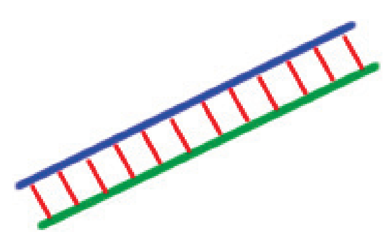
An Archimedes screw might transfer material from the lower triangle to the upper triangle, as shown below-left. Prior to transfer, one might shape with a steel plate blade (orange) that digs into the soil.





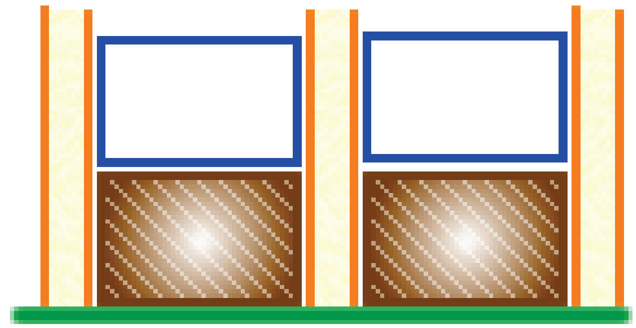
A pile of material (violet) would end up above the soil line and a steel plate retaining wall (purple) might help control it prior to being formed into a proper triangle with an appropriately-shaped solar roller (gold), as shown above-right.

The Tricky Part



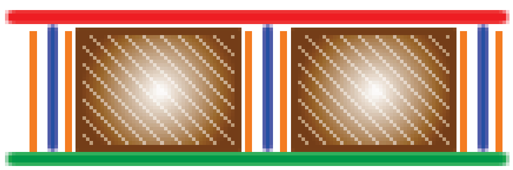
As discussed previously, an anchoring layer (green) is used to secure the solar material (blue). We do not want wind to move it and ultimately tear it apart. Subsequently, we do not place solar material on the prepared surface, and instead place the anchoring layer (e.g. hardware cloth).

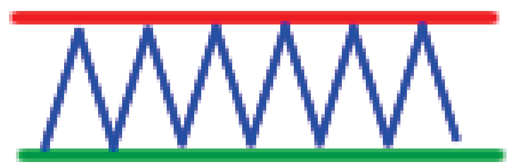
Now it gets a little tricky. We want soil between anchor and solar, and we want linkages connecting the two. Machines that fabricate products in factories, and machines that process fruits and vegetables, often engage in somewhat complicated operations, so we should not be deterred.



Shown to the right is an example approach. Soil from a hopper is transferred above the anchoring layer (brown) and compacted with rollers (blue), while plates (orange) maintain open channels (yellow). Perhaps ~2cm wide channels are spaced every ~16cm. These open areas are used to install the linkages between anchor and solar.

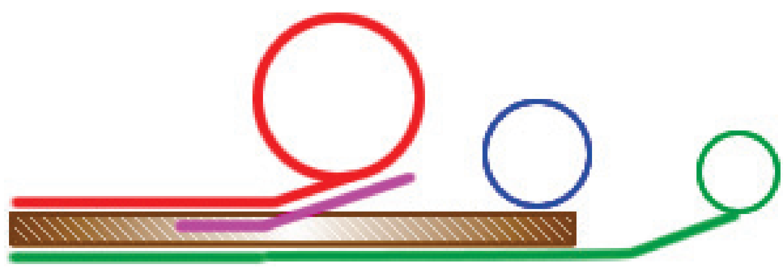
Solar material (red) is placed on top, and connected to underground anchor (green) via linkages (blue), as shown below-left. Linkages might be something like 0.8mm diameter galvanized steel wire. A side view of linkages (blue) is shown below-right.





Putting it All Together

One machine might perform all operations and insure that everything fits together. Shown to the right is a possible side view. The anchoring layer (green) is placed first, followed by soil (brown) which is compacted with a roller (blue). This is followed by the solar material (red). Stitching mechanisms (violet) are inserted into open channels and install wire linkages between the two layers. Post stitching, one might fill the open channels with soil that is blown into position via compressed air.



How Much Does This Cost?

A crane is a somewhat complicated machine and cost $120 per hour. If our machine traveled at 1mph and supported a 6ft width of solar, with a similar cost, then our installation cost would be $0.03 per-linear-ft ($120/5280); which works out to $0.015

per-square-meter of solar material ($0.03*3/6). This translates to 75 micro pennies per Watt ($0.015/200W), which is lower than the traditional solar farm installation costs.

Total estimated costs is $57 per-square-meter of solar material (15+30+10+2), or $0.28 per watt ($57/200W), which is much less than the cost of traditional solar.

$15/m^2	Solar PV wafers, $0.08/Watt
$30/m^2	Fault tolerant internal electronics
$10/m^2	ETFE cover sheet, EVA insulation, back sheet
$2/m^2	Hardware cloth anchoring layer

How does this Differ from Traditional Solar Farms?

Traditional solar farms often tilt panels to face the sun, and space rows far apart to support machines between panels, as shown to the right. Also, weight per-square-meter of solar material is much higher with traditional solar farms than our approach which uses soil for rigidity. Increased weight often translates to increased CO_2 emissions to fabricate the additional material.

Rolled-Solar-Direct-To-Soil Further Research

Simulating the long term effects of wind and rain is an important area of research, since it is not clear this would hold together over time. Also, researchers can explore in more detail machines that install and maintain. And consider the different materials that could be used in the anchoring layer, top solar layer, linkages, riser material, and surrounding apron. Also, researchers can look more closely at Cost-per-Watt and CO_2-emitted-per-Watt for rolled-solar-direct-to-soil vs. traditional solar farm.

Chapter 4) Project Plan

Spawning Industries with Standards based on Free and Open Reference Designs

A mechanical or electrical standard is a document that describes interconnections between components and is accepted by multiple companies. For example, the mechanical design of the 35mm analog film canister enabled makers of film, and makers of cameras, to coordinate. Without this, revenue would be low. There is little incentive for a company to develop a standard, since the world receives the total benefit, while they receive a small portion of that total. Universities avoid free and open since they want to own IP and make money. However, standards are needed to coordinate companies who build machines that fabricate and install. We intend to develop prototypes, make all materials free and open via a CC BY license (to encourage adoption and utilization), and introduce electrical schematics, source code, mechanical drawings, simulations to standard bodies.

Our 10 Year Strategy

How can a relatively small team of researchers develop a complex system that ultimately leads to significant production of solar material directly to building surfaces and to land, worldwide? Answer: Slowly.

Within the next 5 years no one can make money on this technology even if they invest heavily since it requires machines to manufacture, handle, and install solar material; and one cannot develop those machines in short time. Since payback time is long, companies currently will not invest.

The only way to move forward is for university researchers to develop a rough mechanical and electrical design, and give it away for free to encourage utilization. Researchers can do mechanical simulations, perform electrical simulations, develop cost models, build simple mechanical prototypes, develop the basic DC-to-DC converter PCB that is embedded within the solar material, and propose standards that facilitate plug-and-play standardization across multiple industries and companies.

We envision several phases. Phase I: researchers create prototypes and propose interconnection standards. Phase II: standards body formalizes standards (e.g. year's #4 and #5). Phase III: companies make use of standards (e.g. Caterpillar makes installation machines, years #6 and #7). Phase IV: world buys and uses machines. The world needs I before it can do II, needs II before III, and needs III before IV. We aim to do Phase I. This is our 10 year plan.

Project Status as of June 2020

A detailed spreadsheet analysis has been completed that fully models the system in 64 pages of calculations and references. To view, click on the following file and then click on a topic listed within the top 30 rows: GWeinreb_Manhattan2_ResearchNotes.xlsx

A 100 page project summary has been completed and can be accessed by clicking on the following link: Ma2_Solar_RD_Plan.

An electrical schematic of a horizontal array development board has been completed and can be accessed by clicking on the following link: m100_Schematics.pdf.

An initial electrical design has been completed that includes detailed simulations of circuits embedded in solar material. To see these, click on the below "PDF" links.

Buck Converter	o Basic buck converter & gate leakage measure (PDF Schematic, Tina Sim) o Bypass entire converter via Mosfet (PDF Schematic, Tina Simulation) o Current and Voltage Sources in an Array (PDF Schematic, Tina Sim)
Amplifiers	o Main voltage monitor Mux/Amplifier (PDF Schematic, Tina Simulation) o Current Monitor, 14 channel, 0 to 15A (PDF Schematic, Tina Simulation) o Current Monitor, 1 channel, 0 to 15A (PDF Schematic, Tina Simulation)
Calibration	o Create buffered 3.3Vref (PDF Schematic, Tina Simulation) o Create master calibration voltage (PDF Schematic, Tina Simulation)
Power Conversion	o Convert 5.5V power to 4.3V/3.3V power (PDF Schematic, Tina Sim) o Create 3.45V Clamp (PDF Schematic, Tina Simulation) o Convert +3.3V power to -1V power (PDF Schematic, Tina Simulation) o Convert 5.5V power to +3.3V power (PDF Schematic, Tina Simulation)
Power Supply	o 10V Gate Power Supply, 24..75Vin, 2W (PDF Sch, Tina Sim, PDF Report) o 48V-Array-Power to 5V-String-Power, 10W (PDF Sch, Tina Sim, PDF Report)
Power Monitoring	o Detect >3V given 0 to 100Vin (PDF Schematic, Tina Simulation) o Detect >88V given 0 to 100Vin (PDF Schematic, Tina Simulation)
Communication	o System Master Reset, HiPwrOn (PDF Schematic, Tina Simulation) o Communicate between array elements (PDF Schematic, Tina Simulation) o CANbus Interface, Isolated (Adm3050e Datasheet)
Ideal Diode	o Ideal Diode at end of string, 600V/15A (PDF Schematic, Tina Sim)
Microprocessor	o Infineon Xmc4200-f64k256 Webpage

FPGA o Lattice LCMXO3L-640E-5M Datasheet

16bit A/D o Microchip MCP3461T Webpage

Solar BiPV/LiPV Development Teams

Year #1 research is conducted by multiple teams, each of which assumes a different area of responsibility, as described here.

Project Tasks & Milestones

Below is a list of R&D tasks. "Year 1" refers to Sept 2020 to Sept 2021.

- Electrical Design of 300W MPPT DC-to-DC Converter PCB (i.e. electronics embedded in solar material)
  - Create schematic, electrically simulate, and perform spreadsheet analysis -- COMPLETED June 2020
  - Build, Test and Debug breadboard version of circuit (Year 1)
  - Write Software: set up microprocessor, dc-to-dc conversion, MPPT, network CANBus communication, discovery, voltage/current measurement, calibration, digitize waveforms, master controller manages array, measure component properties, estimate component lifetimes, respond to fault conditions (Year 1 and 2)
  - Design, Fabricate, Assemble, Test and Debug PCB (Year 2)
  - Attach to existing 300W solar panels and test outside in array configuration (Year 3)
- Research the effect of silicon bent in storage on lifetime and efficiency
  - Store solar PV components of different types (e.g. mono Si) in different bend states, at different temperatures, and periodically measure efficiency. For example, study storage radii of 0.5m, 0.7m, 1m, 1.3m, and 1.5m (Year 1).
- Mechanical Design of Rollable Solar PV Material Direct to Plywood (BiPV)
  - Design and Analyze material mounted directly on plywood (Year 1)
  - Simulate 30 years of UV, wind, rain, thermal cycling, hailstone impact, heat flow from PCB and solar cells to top surface, and heat flow from hot fault condition (i.e. fire resistance). (Year 2)
  - Measure thermal properties with small prototype: e.g. 3 x 3 solar cells, dummy PCB embedded in solar material, power resistors mounted on pcb and powered by power supply that supports 6W (normal) and 300W (fault) of heating, mount on 2 x 3ft plywood. (Year 1)

- Test overlapping joint with small prototype: e.g. 2 overlapping solar strips, each 12 x 24 inches, bound by internal and external rails, test with water and wind. (Year 1)
- Explore machines that fabricate, handle and install material (Year 3)

- Mechanical Design of Rollable Solar PV Material on Soil (LiPV)
  - Similar to BiPV above, yet mount on land
  - Mount non-solar material (e.g. sheet metal) directly onto soil, add markings on top surface, photograph periodically, add "rain" water, possibly add wind, and observe movement due to erosion and wind. (Year 1 and 2)
- Mechanical Design of Rollable Solar on Agricultural Farms, co-locate with crops
  - Similar to LiPV above, yet mount on land, next to agricultural crops (Year 1)
  - Design & Simulate irrigation system that directs water from solar to crops (Year 2)
  - Design safety system that turns off solar when worker enters area (Year 2)
  - Explore farm tractor attachments that handle, install and maintain rollable solar. (Years 1, 2, and 3)
- Build larger prototypes, more testing, improve fault tolerance and monitoring. (Years 2 and 3)
- Propose mechanical, electrical, software, connector, and communications standards. (Year 3)
- Propose new chapter in the National Electric Code (NEC) that regulates Building Integrated PV (BiPV) and Land Integrated PV (LiPV). (Year 3)

Research Teams

Year #1 research is conducted by multiple teams, each of which assumes a different area of responsibility, as described here.

Conclusion

In conclusion, the solar community needs to think more like Ford and Deere;
and less like Rolls and Royce.

Solar Electrical System via Networked 300W DC-to-DC Converter

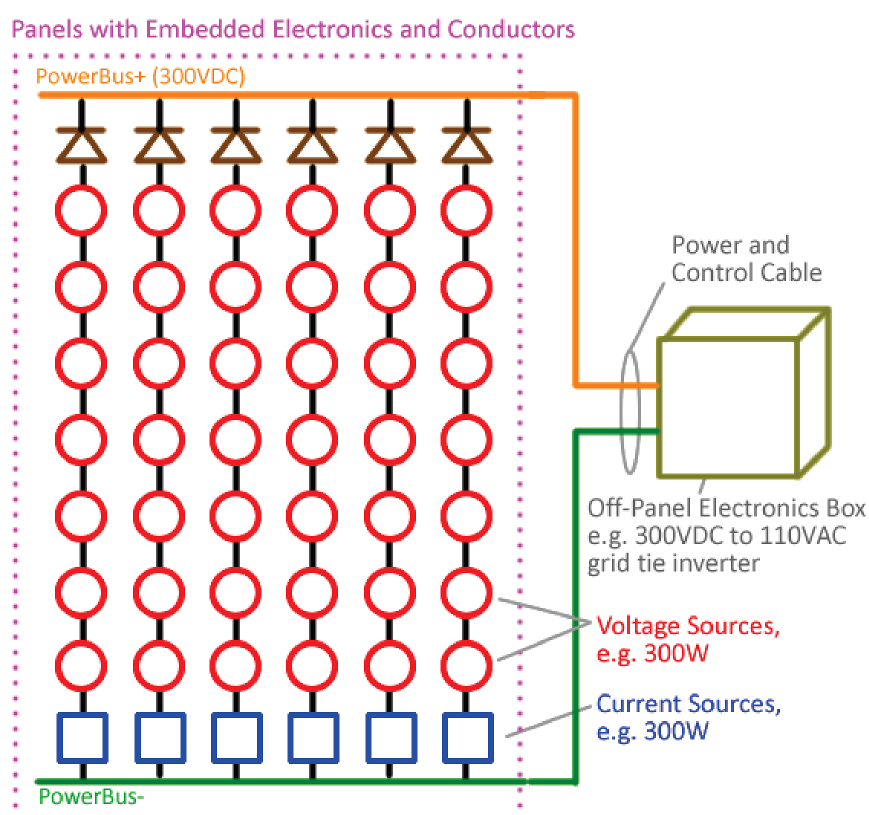
One of the lowest cost power converter topologies is the buck converter. It does not use a transformer and often has efficiency of ~98%. In theory, one could allocate a 300W DC buck converter every 1.5 square meters of PV material for purposes of MPPT (maximum power point tracking), fire prevention (turn off in event of fault), and degradation management (e.g. shading one area does not affect entire system).

A typical string inverter (e.g. 400VDC-to-110VAC, 4kW, 20 square meters of PV solar) has two stages. Stage#1 is DC-to-DC, does MPPT, and outputs a high DC voltage. Stage #2 takes the output of stage #1 (e.g. 400VDC) and converts it to AC (e.g. 110VAC).

Our plan is to embed many ~300W circuits inside the solar material and combine them to produce a high DC voltage that is routed to the 2nd stage of an off-panel string inverter. In other words, create a steady ~400VDC while still inside the panels, and convert to something more useful in an off-panel box (e.g. to 110/220VAC grid tie for houses, to 440VAC for commercial buildings, or to 660...1440VAC for solar farm). The alternative is long strings which are vulnerable to one region of degradation that limits the entire string.

Low Voltages Component are Low Cost and Low Height

The illustration to the right shows how low cost 300W MPPT converters could be combined to produce one steady high DC voltage, for an off-panel box of electronics.



- Red circles are 1.5m^2 of solar PV connected to 300W dc-to-dc converters with voltage source output (e.g. 50VDC output, supports ≤ 7A current).
- Blue squares are 1.5m^2 of solar PV connected to 300W

dc-to-dc converters with current source output (e.g. 6A current source output at ≤ 60V).

- Green is PowerBus- at approximately earth ground.
- Orange is PowerBus+ at ~400VDC.
- Brown are ideal diodes implemented with 600V MOSFETs.
- The PowerBus+- (e.g. 400VDC/36A/14.5kW with 48 x 300W circuits) feeds a 400VDC to 110VAC grid tie converter (e.g. 2nd stage of 14.5kW string inverter with 110VAC output).

The voltage sources maintain a constant voltage independent of current (e.g. 37.5V, ≤ 8A) while one current source per string sets the voltage to support the desired current (e.g. 7.5A, ≤ 40V). A buck converter can be set up to regulate voltage or current, or both, as noted in this video. Subsequently, one could set voltage and current limiting within each 300W circuit via software.

Blue elements are the first in the string, and are at earth ground; whereas others (i.e. red) are floating w.r.t. earth.

Each of the 300W elements (both Red and Blue) contain an internal bypass mosfet that enables one to replace the element with a 5mΩ resistor. This occurs if their processor does not boot, or PV provides no power.

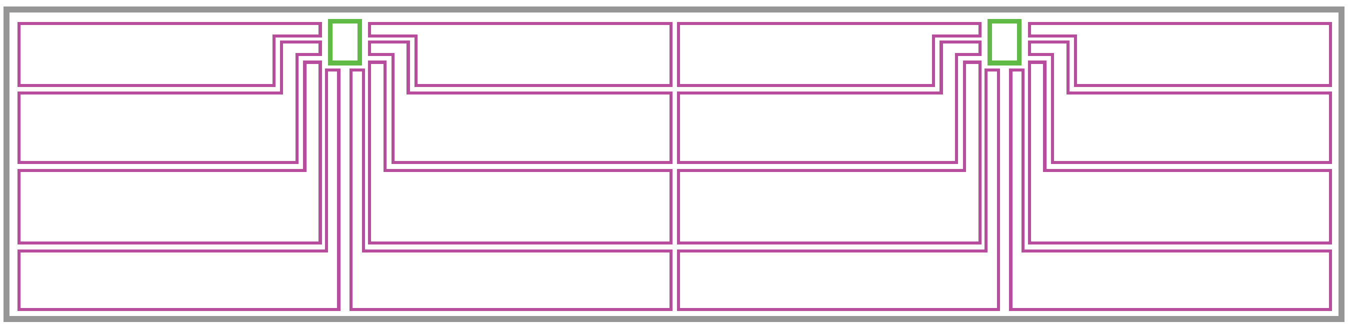
An ideal diode is placed above the last element in each string (i.e. near 300VDC). Placing the diode here enables mosfet bypass switches to engage and pull panels close to earth ground (e.g. instead of floating at 300VDC); allowing them to be stored in a safer configuration. This circuit is somewhat costly yet we only have one per string (e.g. four 600V 100mΩ #STB36N60M6 MOSFETs cost $8 total and a 5V to 12V #R1SE-0512 power supply cost an additional $2.30).

If the load changes suddenly, we would want the system to respond in a reasonable manner. CANbus is capable of broadcasting a message to all DC-to-DC converters on the network in < 10uSec. Exactly how this works deserves further consideration and presents a challenge for researchers.

Alternatively, one might look at longer strings and less electronics embedded in the material. Unfortunately, any degradation of electrical current along a string limits current within the entire string. Subsequently, long strings are often problematic.

Multiple 300W Converters on One PCB

To reduce cabling, connectors and harnesses; one might place *multiple* 300W converters on one PCB. For example, if one routes eight 300W sections of solar to one PCB (light green in below illustration), then one might have 2m x 12m (24m^2) of solar for each PCB, as illustrated below. The below picture shows 2m x 24m; however, on land, one might unroll 2m x 96m with 8 large embedded PCB's. The PCB's are placed close to the edge to make them more accessible. In theory, electrical cable between PCB's could be along the edge of each strip, accessible from this edge. If working with solar direct to soil (LiPV), this edge is probably accessible by a worker. However, if on plywood, this edge is not easily accessed unless one lifts up the strip above, which is tricky.



Alternatively, one could gain access to PCB's via a hatch that sits on the surface, similar to a vent, shown below.

If one does not have physical access to the electronics, then fault tolerance would be required to keep the electronics working well over a long period of time, which is an additional challenge.

Vertical or Horizontal Array?

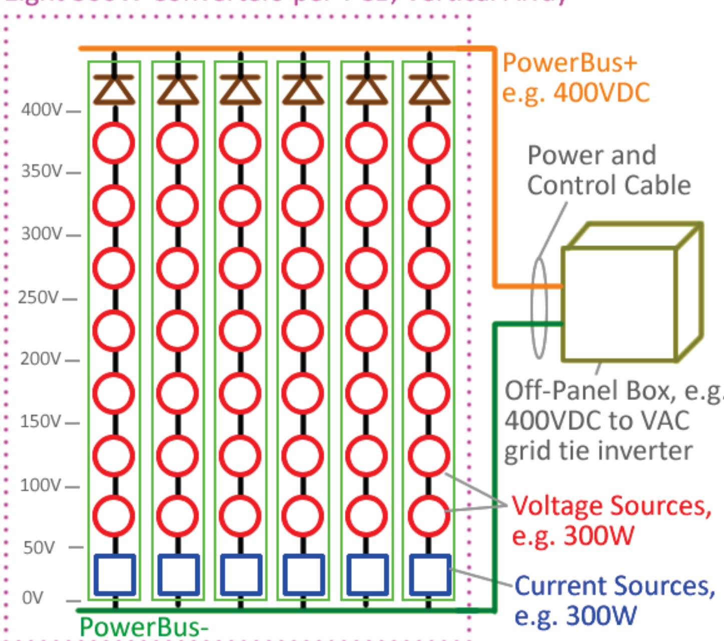
The below illustration on the left shows 400V strings with eight 300W elements per PCB, combined in parallel (one current source and seven voltage sources per PCB). The light green vertical rectangles each represent a PCB. We call this a "vertical array", since the elements on each PCB are arranged vertically in the illustration.

Also, one might consider organizing 300W elements horizontally, as illustrated below and to the right. In this case, eight 300W elements combine in parallel (one voltage source and several current sources per PCB). The advantage is all elements on each PCB are at the same voltage level; whereas in the vertical array, one needs isolation power supplies and isolation CANbus transceivers between each converter, and common circuitry needs to be duplicated at each converter.

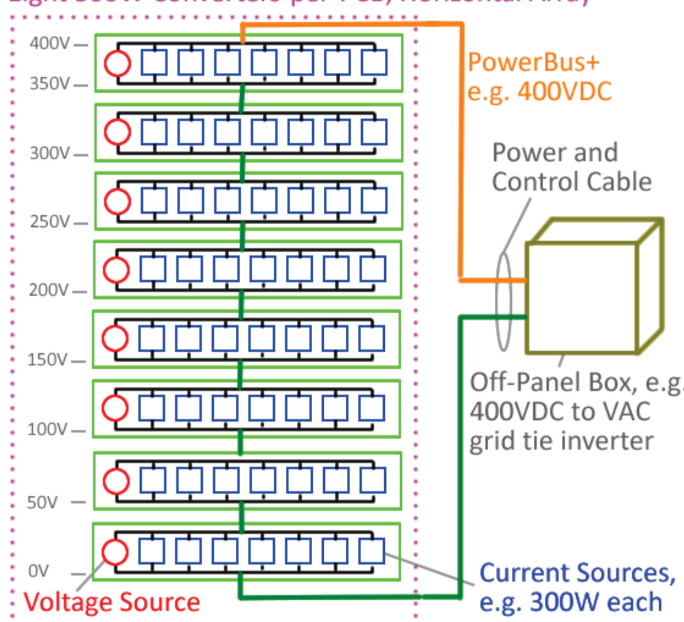
It is easy to combine current sources in parallel on one PCB. However, current sources typically do not combine in series, which we are doing here between each layer (instead, one typically combines *voltage* sources in series). In our illustration, we have a voltage source set the voltage between each layer (red circle) and then the current sources augment the current. For a simulation that shows this (working), see PNG schematic and/or Tina simulation files. Another approach might be to utilize current controlled current sources (CCCS).

It is not clear Horizontal is feasible, since it would need to respond to fast load changes, among other challenges. In summary, if researchers can figure out how to make horizontal arrays work, we would see a nice cost reduction.

Eight 300W Converters-per-PCB, Vertical Array



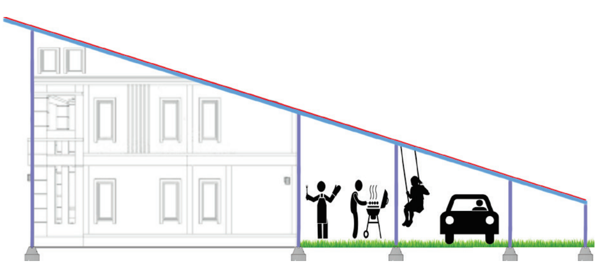
Eight 300W Converters-per-PCB, Horizontal Array

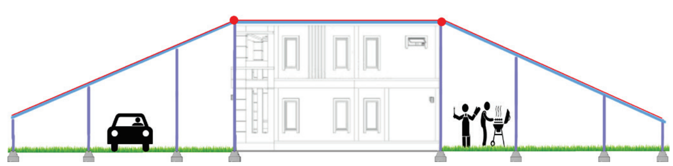


Chapter 6) DC-to-DC Optimizers Embedded into Solar Material

Large 2 x 10meter 4kW panels With Embedded Electronics -- Where Do They Go?!

In theory, large ~2 x 10 meter panels can stack on the back of a flatbed truck drop in by crane. One might place these in a parking lot, above a carport, in a solar farm, or on a commercial roof, as illustrated below.



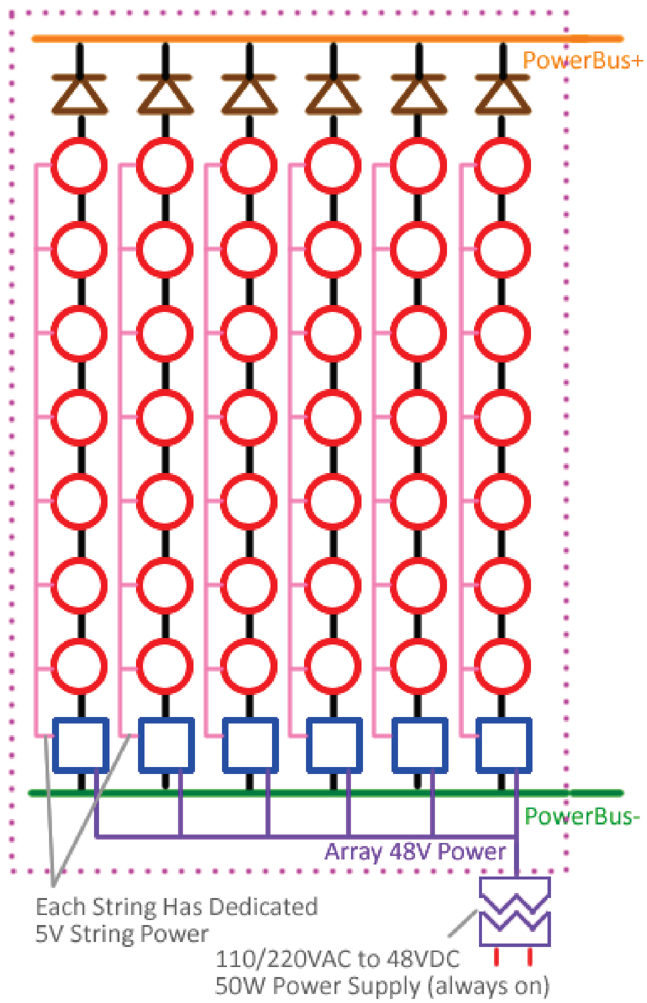


The advantage of large solar panels with embedded electronics over traditional 3x5ft panels with external electronics is as follows:

- Less labor installation cost.

- One can more easily interconnect DC-to-DC converters (i.e. "optimizers") with multiple internal wires. This improves communication, which enables more features (e.g. balance multiple strings in parallel, reliably set voltage/current limits for each element, bypass non-performing elements, fire control, emergency shut-down, and ground fault detection).
- More reliability due to fewer exposed connectors and cables.

48V-Array-Power and 5V-String-Power



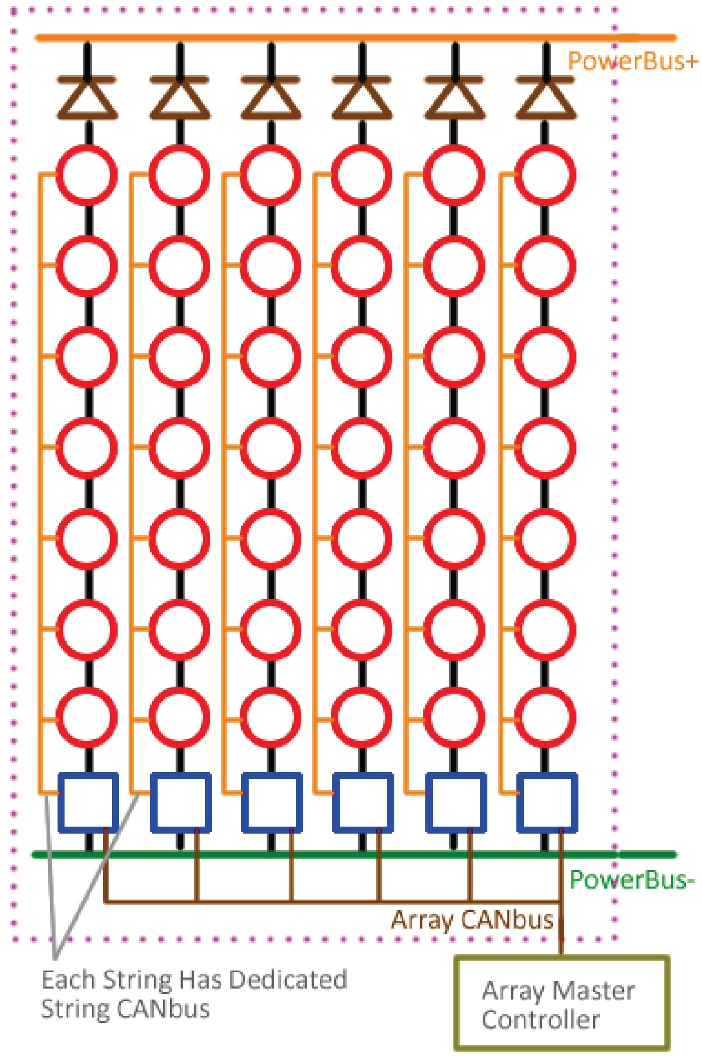
As shown to the right, an external 48V array power supply pushes 48V (purple in picture) into the large panel(s). Subsequently, one can communicate w/ each processor even if PV power is down. This helps with configuration, testing, responding to fault conditions, and responding to sudden interruptions in PV power. Each 1st string element 300W PCB (i.e. current source output, referenced to earth gnd, blue in picture) contains a 48V-to-5V non-isolated regulated dc-to-dc 10W converter. This converts 48V-Array-Power to dedicated 5V-String-Power (fuchsia color in picture), and routes to all elements in a string (red in picture, voltage source output, floating wrt earth ground). 5V-String-Power is used by CANbus transceivers, microprocessors, and analog measurement circuitry. Each 300W PCB converts 5V-String-Power to 3.3V via an isolated regulated 500mW power supply.

5V-String-Power does not drive mosfet gates. Alternatively, they are driven with a 16...84V PV power to 14V non-isolated regulated 2W dc-to-dc converter, one per 300W PCB.

Array-Power is a higher voltage (e.g. 48V) since we want to be more resilient to voltage drops across long wires. Whereas String-Power is 5V since it directly powers the earth side of isolated CANbus controllers, which are looking for 4.5 to 5.5V.

We provide a dedicated 5V to each string, instead of 5V to multiple strings, since we do not want a system wide failure in the event that String-Power goes down.

Array-CANbus and String-CANbus



As shown to the right, we handle CANbus in a manner similar to power. An Array-CANbus network (brown) connects the off-panel Master Controller (gold) to all 1st string element 300W PCB's (blue).

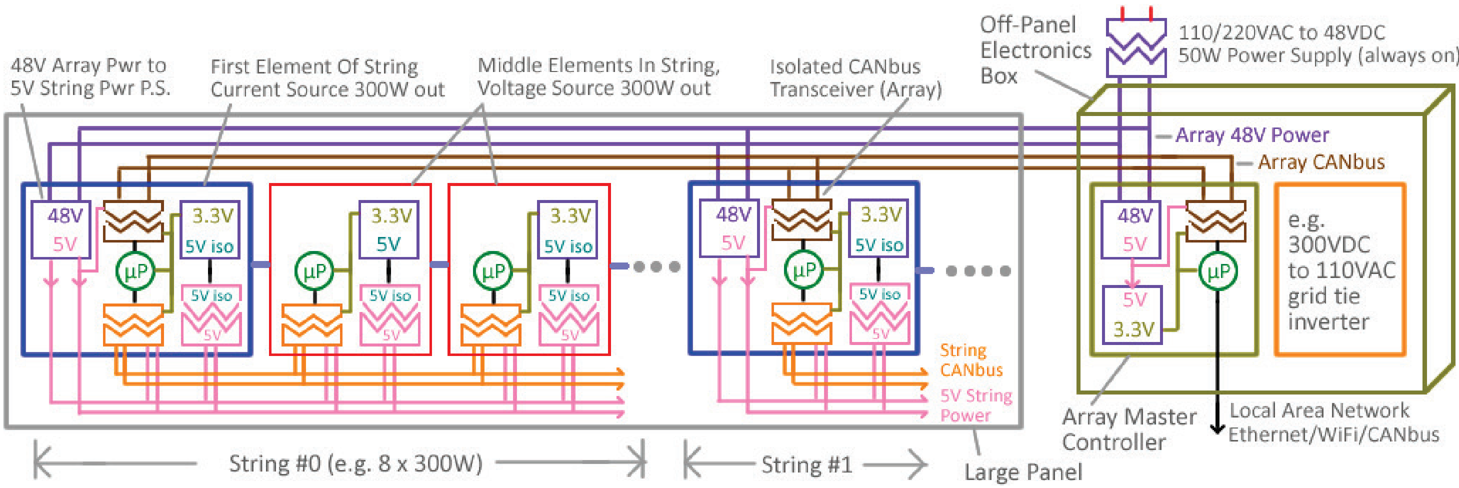
Each string has its own CANbus network (orange) that enables all processors within that string to communicate.

The master controller might broadcast a message to all 1st string elements (blue) and tell them to gather temperatures of all string PCB's. Each 1st element in turn would send a message to their string PCB's requesting that they measure and return a temperature. Then, each 1st string element would pass data back to the master controller, in one consolidated data block.

There are several advantages to dedicating a CANbus network to each string. One is it reduces the amount of traffic on the bus (e.g. 60 devices on one bus might load down bus too much). Another is it makes the system more resilient in the event a CANbus network goes down (which would effect a string, and not the entire system).

Array of 300W Converters

One might implement each ~300W converter with a $3.30 #XMC4200F64K256 microprocessor that does buck conversion and communicates with the entire system via CANbus, as illustrated below.



Each ~300W element floats with respect to earth ground, between 0V and 400V (e.g. microprocessor COM pin might be at 100VDC with respect to earth ground if it was the 3rd 50VDC element in an 8 element 400VDC string). To float the PCB, one might utilize a $2 isolated CANbus transceiver (e.g. #ADM3050e or #ISO1042) and an isolated 5VDC-to-5VDC power supply module (e.g. #PDSE1-S5-S5-S, $1.56).

Alternatively, one might try to implement a more expensive isolated 300W fly-back transformer and keep the solar PV output- wire at earth ground to reduce the risk of shock hazard (i.e. keep solar outer surface at < 60V w.r.t. earth ground). The disadvantage of this approach is one would need optical isolation between d/a converters and comparators on the secondary side while the microprocessor is on the primary side; which is more costly. Solar material on vertical walls might be willing to incur this additional cost since it is more difficult to get a shock from 60V then 400V. Shock hazard is of greatest concern when close to an open window or close to ground level.

At the right side in the above illustration, we have an off-panel grid tie 400VDC-to-110VAC inverter which connects to a local area network via something like Wi-Fi, wired Ethernet, fiber Ethernet and/or CANbus (each of which has their advantages and disadvantages).

A master controller PCB sits inside the off-panel box and coordinates all embedded-panel processors and all off-panel processors. CANbus is selected because it is embedded into many low cost $1 and $2 processors, and an isolated CANbus transceiver only cost $2.

One ~5V (or higher) power supply (upper right corner in above illustration) powers all processors in the system (e.g. 0.5W per 300W converter).

Might we adapt our 300W Circuit to output AC instead of DC?

Researchers might look at adapting the 300W circuit to produce AC instead of DC; and eliminate the need for an off-panel box of electronics. However, one needs to deal with energy storage while the AC sinewave is at the zero crossing.

If one stores 300W with a capacitor that is charged 50V/6A for 8mSec, they would need 1000uF of capacitance, for example ($I = C * dV/dt = 1000e\text{-}6F * 50V / 8e\text{-}3Sec = 6A$). Chip capacitors would be too expensive. Electrolytic cost might be reasonable (e.g. 7 capacitors, where each is 150uF, 16mm tall, 12mm diameter, $0.41, ESR 130mΩ @ 20°C and 2500mΩ @ -40°C, #EMHS101ARA151MKG5S). However, at colder temperatures, ESR increases and this would lead to excess heating (e.g. $1Watt = i^2 * r = 1A^2 * 1\Omega$ at 0°C per capacitor). Electrolytic capacitors are typically designed to last 5000 hours at 85°C and are prone to failure; therefore one might refrain from their use.

Also, AC output might require one stage to push energy into these storage capacitors and another stage to pull it out, which entails more components and more cost.

Parts and Labor Cost for each 300W Converter

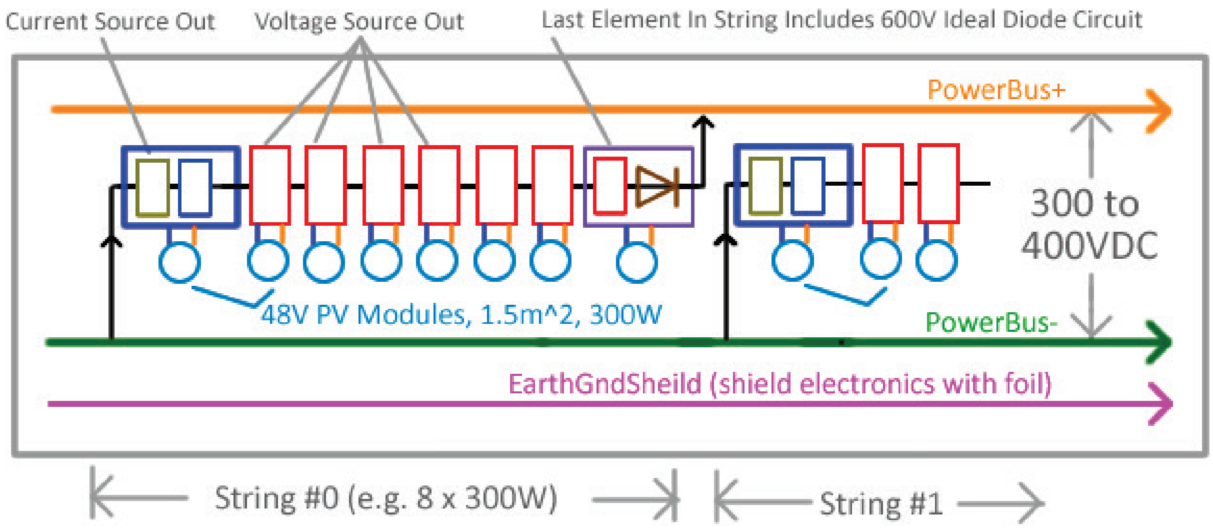
The parts and labor cost to make each 300W converter is estimated at $33, which works out to $0.11 per Watt. This includes $19 for primary components; $4 for miscellaneous components; and $10 for assembly/testing labor, raw PCB, and enclosure. PCB size is estimated at 3" x 3" (8 x 8 cm). For more details, search "300W DC-to-DC Converter" in this file.

Below is a list of primary parts.

		Cost 1K qty ($)	Qty/PCB	Total Cost/PCB $	Total Area mm^2	Description
Microprocessor		$ 2.17	1	$ 2.17	49	Microprocessor: 32bit, M4, 80MHz, 20KB ram, 64KB flash, 3.3V, DAC, ADC, Timers,
		$ 1.90	1	$ 1.90	63	CANbus Trancvr: Isolated, 5700V, 1.7V to 5.5V uP pwr, 5V CANbus pwr, Ri-8 packa
Buck Converter		$ 0.85	4	$ 3.40	624	Ind: 56uH, 4A rating, 0.056Ω at DC, 13 x 12 x 6.5mm, shielded, wirewound, #HCM:
		$ 0.12	18	$ 2.16	144	Cap: 2.2uF, 100V, 1210, $0.12, #1276-CL32B225KCJSNNF
		$ 0.68	5	$ 3.40	335	Mosfet: 100V, 0.005Ω, 92A, DPAK (7x10mm), #TPH4R10ANL,L1Q
		$ 0.10	1	$ 0.10	22	Zener: 82V, On: 82V @ 5mA, Off: 62V @ 1uA, 18mA max, DO-214AA (SMB), #1SMI
Power Supply		$ 1.56	1	$ 1.56	70	DC-to-DC converter: 3.3Vout, 5%, 30 to 300mA out, 4.5 to 5.5Vin, Isolated, 1W, PC
		$ 0.20	1	$ 0.20	9	Voltage Reg: 2.9Vout, 300mA, 3% out accuracy, 100mVin headroom, 5mΩ esr min
		$ 0.93	1	$ 0.93	9	Voltage Ref: 2.5Vout, >2.8Vin, 0.08% init acc, 8ppm/C mx, 300uA quies, 4.8uV .1 tc
		$ 0.08	4	$ 0.32	23	Ind: 6.8uH, 570mA rating, 0.5Ω at DC, 2.4 x 2.4 x 1mm, shielded, wirewound, #NRI
		$ 0.03	5	$ 0.13	13	Cap: 10uF, 10V, 0805, $0.026, #CL21B106KPQNNWE
Amps	2.5V uP Apwr	$ 0.22	1	$ 0.22	20	Op Amp: 1x amp, 25pA @ 85C typ, 4pF, 2mVos mx over temp, 0.5uV/C typ, 10MH
	Vin Shunt	$ 1.12	1	$ 1.12	9	Current Sense Amp: 0 to 110V, G=200, 600KHz, 25uVos mx, 0.25uVos/C, 0.25% gai
		$ 0.12	1	$ 0.12	20	Shunt Resistor: 1mΩ, 2512, 1%, 50ppm/C, 3W, #CSRL3-0R001F8
	Load Shunt	$ 0.20	1	$ 0.20	20	Op Amp: 2x amp, 25pA @ 85C typ, 4pF, 2mVos mx over temp, 0.5uV/C typ, 10MH
		$ 0.12	1	$ 0.12	20	Shunt Resistor: 1mΩ, 2512, 1%, 50ppm/C, 3W, #CSRL3-0R001F8
		$ 0.04	4	$ 0.15	5	Res: thin film, 0.1% acc, 25ppm/C, 0603, 75V, 0.063W, #ERA-3AEB **
	Vout Voltage	$ 0.22	1	$ 0.22	20	Op Amp: 1x amp, 25pA @ 85C typ, 4pF, 2mVos mx over temp, 0.5uV/C typ, 10MH
		$ 0.04	1	$ 0.04	1	Res: thin film, 0.1% acc, 25ppm/C, 0603, 75V, 0.063W, #ERA-3AEB **
		$ 0.07	1	$ 0.07	5	Res: thin film, 0.1% acc, 25ppm/C, 1206, 200V, 0.25W, #RNCF1206BTE **
	COM wrt EarthGnd	$ 0.22	1	$ 0.22	20	Op Amp: 1x amp, 25pA @ 85C typ, 4pF, 2mVos mx over temp, 0.5uV/C typ, 10MH
		$ 0.04	1	$ 0.04	1	Res: thin film, 0.1% acc, 25ppm/C, 0603, 75V, 0.063W, #ERA-3AEB **
		$ 0.03	4	$ 0.12	20	Res: thin film, 0.5% acc, 25ppm/C, 1206, 200V, 0.25W, #RT1206DRD07 **
External 8:1 Mux		$ 0.35	1	$ 0.35	35	Mux: 8:1, 5nA max @ 85C, 108Ω, 5.5Vpwr, 16-TSSOP, #NLAST4051DTR2G
		$ 0.11	1	$ 0.11	35	Mux: 8:1, 400nA max @ 85C, 140Ω, 10Vpwr, 16-TSSOP, #74HC4051PW,118
		$ 0.12	1	$ 0.12	5	Switch: SPST, 10nA max @ 85C, 50Ω, 5.5Vpwr, SOT-70-5, #NLAST4501DFT2G
		$ 0.22	1	$ 0.22	20	Op Amp: 1x amp, 25pA @ 85C typ, 4pF, 2mVos mx over temp, 0.5uV/C typ, 10MH
		$ 0.14	1	$ 0.14	1	Res: thin film, 0.1% acc, 10ppm/C, 0603, 75V, 0.063W, #RT0603BRB07 **
		$ 0.22	1	$ 0.22	20	Op Amp: 1x amp, 25pA @ 85C typ, 4pF, 2mVos mx over temp, 0.5uV/C typ, 10MH
Conditioning						
	Temperature	$ 0.05	2	$ 0.10	3	Thermistor: 10K ohms @ 25C, 1% resistance accuracy, 0603, #NCU18XH103F60RB
	0.3V, 2.2V	$ 0.68	1	$ 0.68	5	Res Network: thin film, 1K/10K/1K/10KΩ, 0.05% ratio acc, 7.5ppm/C ratio drift, 0.1
	2.5V	$ 0.14	1	$ 0.14	1	Res: thin film, 0.1% acc, 10ppm/C, 0603, 75V, 0.063W, #RT0603BRB07 **
	75V	$ 0.07	2	$ 0.14	10	Res: thin film, 0.1% acc, 25ppm/C, 1206, 200V, 0.25W, #RNCF1206BTE **

Multiple DC-to-DC Converters Form 400VDC Strings that Feeds a Common bus

As shown below, a common 400V power bus (PowerBus+, PowerBus-) is supported by multiple strings, where each string consists of eight 300W elements in series, 37.5V per element. One might have 1 to 10 strings in each large panel. A 2 x 10 meter panel that stacks on the back of a flatbed truck might have 2 strings, for example.

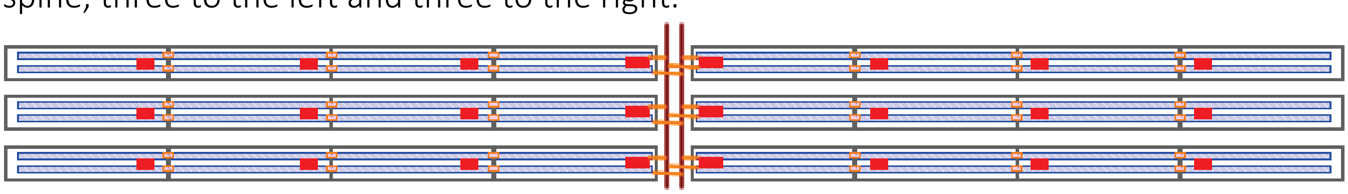


A 1.5m^2 solar panel (aqua circle in above illustration) is connected to each 300W converter.

Large Panels Can Be Connected Together

One might bus together multiple large panels, as illustrated below.

For example, at a solar farm one might join four 2x10 meter 4kW panels to form a 16kW system which attaches to a common spine (brown in below illustration) that further transfers power. The below 96kW system shows 6 of these 16kW systems joined to the spine, three to the left and three to the right.



Four Different PCB's

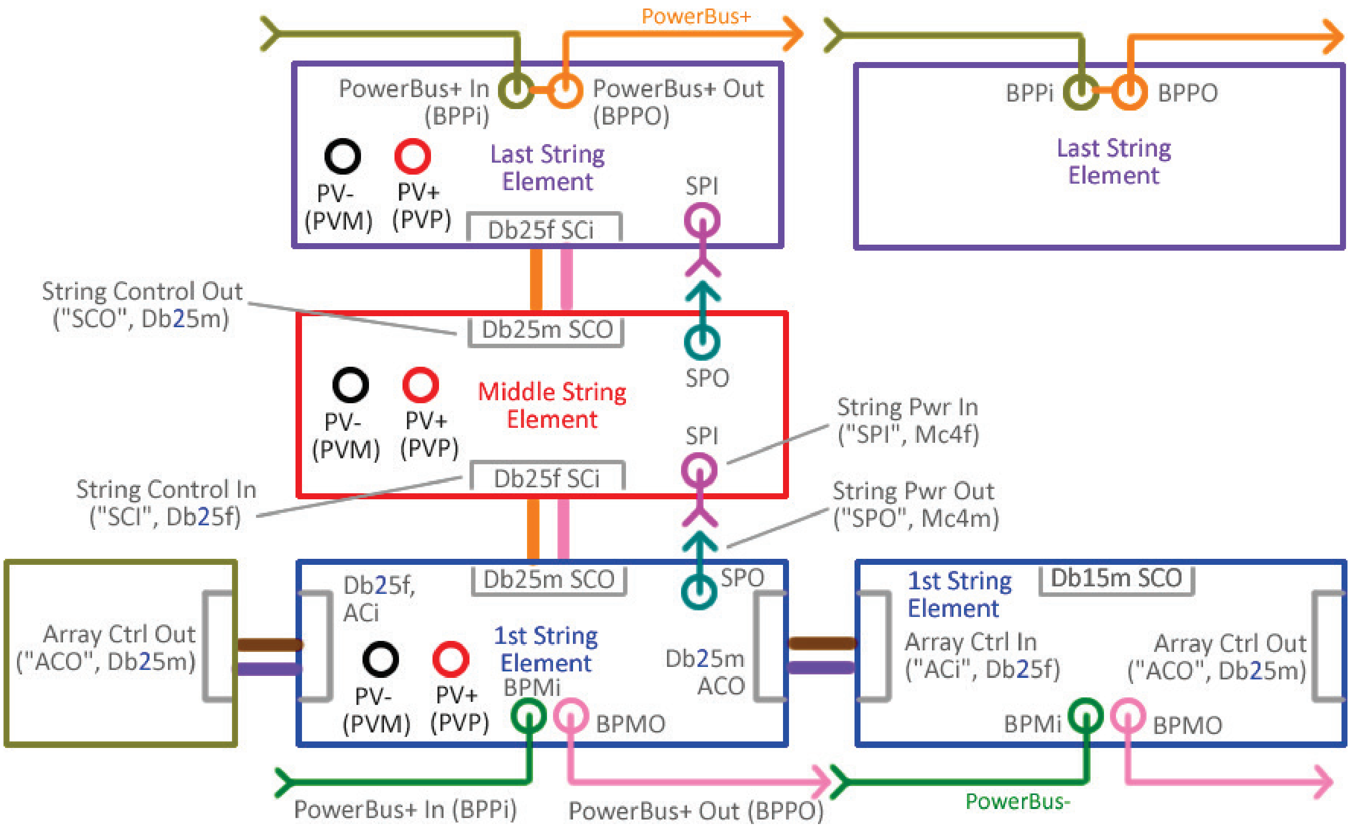
Our system involves four different PCBs:

- The first converter in the string (blue) includes a 48V-Array-Power to 5V-String-Power dc-to-dc converter, includes an Array-CANbus interface (in addition to String-CANbus), provides a current source output, is referenced to earth ground (not floating), measures voltages on shield for ground fault protection), and contains connectors that enable it to connect to other 1st string elements (one can do this since they are all referenced to earth gnd).
- The middle elements in each string (red) provide a voltage source output, talk with the 1st string converter via a local string CANbus network, and float with respect to earth ground.
- The last element in each string (purple) contain a series diode (brown) to maintain current flow in one direction, includes connectors that interface to PowerBus+, includes circuitry that enable one to measure PowerBus+. It also includes a 12V isolated power supply that powers the upper ideal diode (connected to PowerBus+) and can power Bypass Mosfets within a string when there is no PV power (can pull all panels to earth ground).
- The Master Controller resides in an off-panel box of electronics, it interfaces with the off panel DC-to-AC inverter, it knows system load, it coordinates all array elements, and it communications with the local area network.

Development Platform

Initially, we design and build a development PCB that satisfies the requirements of all four positions and use it to test the entire system. This PCB contains additional diagnostics circuitry and is not concerned with surface area, volume, and cost (which are addressed in future versions).

The development PCB includes DB-25 and MC4 connectors that enable one to implement all four positions; as shown below. This means that this one PCB would be a bit bulky with two four DB-25 (SCi, SCO, ACi, ACO) and four MC4 connectors; yet bulk is ok with this version.

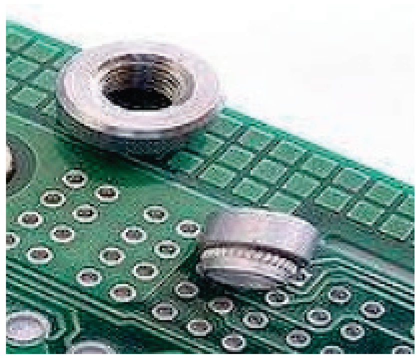


DB25f-to-DB25m 10ft cables are sold by Comtop for $2.35 each in 60 quantity, for example. Typical connectors cost $1 (e.g. #D25P33E4GX00LF) and each pin is typically rated for 3A.

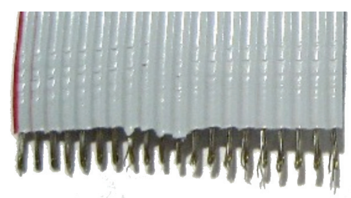
48V-Array-Power utilizes ~1A and could be placed on 6 pins for 48Vpwr+ and 6 for 48Vpwr-. 5V-String-Power involves ~2A and could be placed on 6 pins for 5Vpwr+ and 6 for 5Vpwr-. One needs to be careful with female DB25 connectors. Some are cheap and included flimsy female contacts that do not hold up well with higher currents. Amphenol FCI #D25S33 is decent.

One can also utilize two pins for each signal, so that if one goes down, the other continues to conduct. If one is heavily dependent on connectors and one bad connection can take down a large system, then two pins per signal is a wonderful method to decrease failure rates.

MC4 is a standard solar power connector, is typically rated for 30A, and can easily route ~8A between each string element. One could place broaching fasteners (threaded standoff pressed into PCB and soldered to PCB top layer) to create a point of contact for a crimped wire terminal. To make a pigtail (wire with MC4 connector on one end and crimped terminal on the other), one could cut an MC4 adaptor cable in half and attach a terminal to each end. These could easily be bolted to broaching fasteners.

Routing of power between strings is a bit more complicated, since one might be looking at high currents (e.g. 8 strings x 8A each = 64Amps).



Our development board uses somewhat bulky connectors (yet low cost). A production system, with electronics embedded into solar material might utilize ribbon cable with solid conductors that solder directly to PCB.

Two Wiring Harnesses Could Implement Our System with Existing 48V 300W Panels

We are two wiring harness away from implementing our proposed electrical system with existing 3x5 foot 300W solar panels and traditional installation techniques. Shown below is a traditional PV panel with a box of electronics attached to its rear surface, which could be our 300W circuit, in theory. If one knows the size of the panels (e.g. 3x5ft) and knows how they are arranged (e.g. 4 across and 2 high for a total of 12ft wide and 10ft high), then they could create a String Harness to connect these together. The harness would support 2 high current wires (e.g. 8A, 0 to 400V), 3 medium current wires (e.g. 5Vpwr+-, EarthShield), and 4 signal wires (e.g. EarthSense, HiPowerOn, CANbus H/L).

To increase reliability, we might *not* cut each wire at each node (and be dependent on connectors). Instead, we might remove plastic shielding from each wire and solder the connector terminal to the internal metal connector. Also, we might utilize screw force with heavy power wires. Shown above is a worker at a wiring harness assembly table (this is a real thing).

A String Harness would support a string with 8 panels. One would also need a Power Bus Harness to connect together multiple strings; and connect those to the off-panel box of electronics. Exactly how this works deserves further consideration.

$3 Microprocessor Provides Power Conversion and Communications

The $3.30 #XMC4200F64K256 microprocessor supports communications (e.g. CANbus) and power conversion (e.g. DC-to-DC converter). Xmc4xxx comparators include filtering, blanking and clamping capabilities as well as a DAC for automatic reference or slope generation. If we place one of these processors every 300W, for example, then microprocessor cost would work out to $0.007 cost per Watt. Most home installations are $3 per Watt total, parts and labor. A 2 x 10 meter 4kW panel might include thirteen 300W embedded converters, for example.

The Xmx4200 processor includes two CCU4 timer units (8x 16bit timers), one CCU8 timer units (4x 16bit timers), one HRPWM high resolution pulse width modulation unit (d/a and analog comparators), two VADC 12 bit a/d' s with 8 channels each, two 12bit DAC d/a converters, two CANbus controllers, and a USB interface (e.g. for development).

For more details, download the 2100 page Xmc4xxx User's Manual to your computer and use left-side navigation to explore: CCU4, CCU8, HRPWM, VADC (a/d) and DAC. Also, see the 100 page Xmc4xxx data sheet.

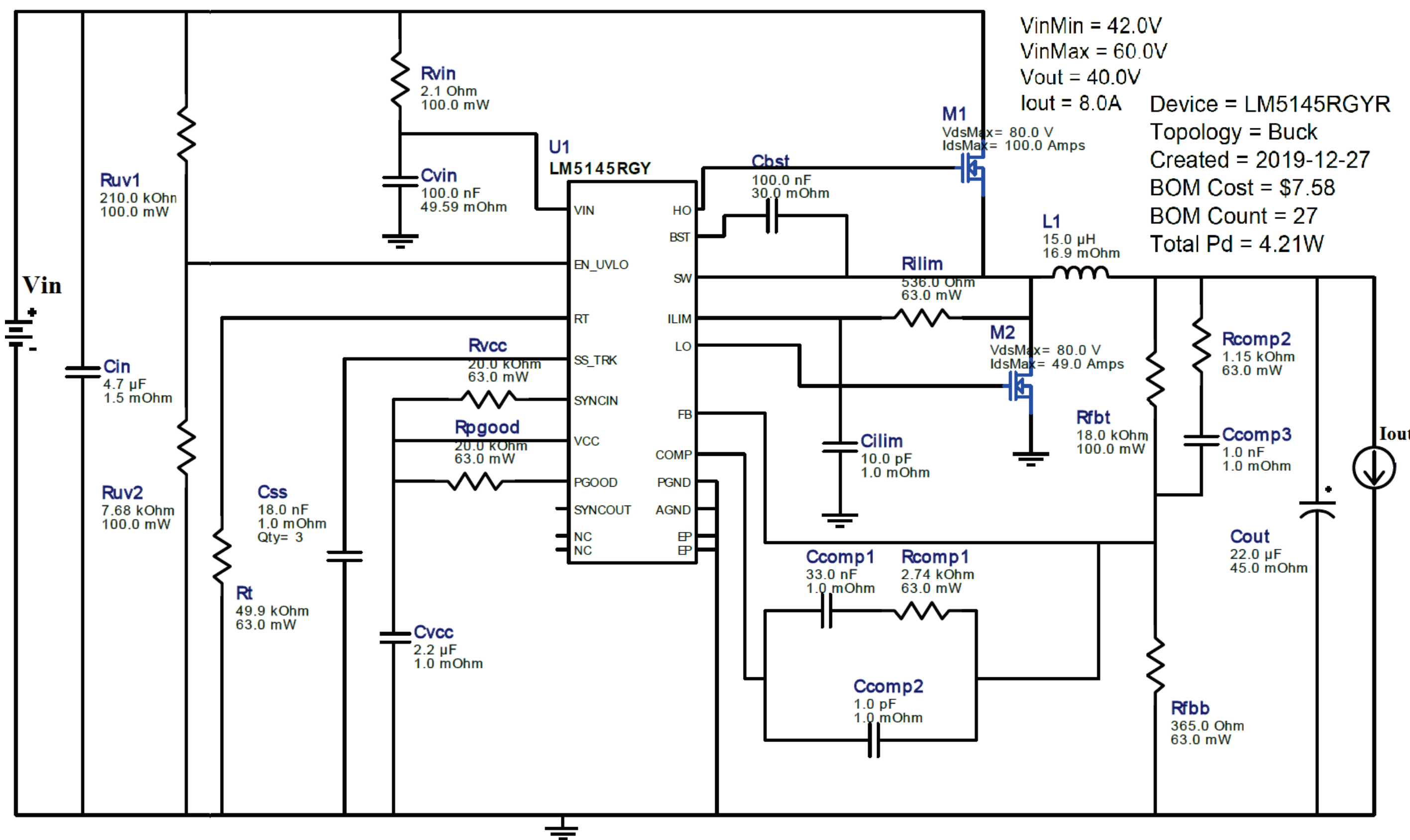
For a summary of Xmc4xxx resources download the 100 page [Manhattan 2 Next Generation Building Automation and Control R&D]() plan to your computer and use the left-side navigation to explore: "Infineon Processors" and "Xmc4xxx Power Conversion Application Notes".

For a summary of power applications, see the Xmc4xxx [power conversion]() presentation.

For a list of resources, refer to this Infineon Xmc4xxx [product web page]().

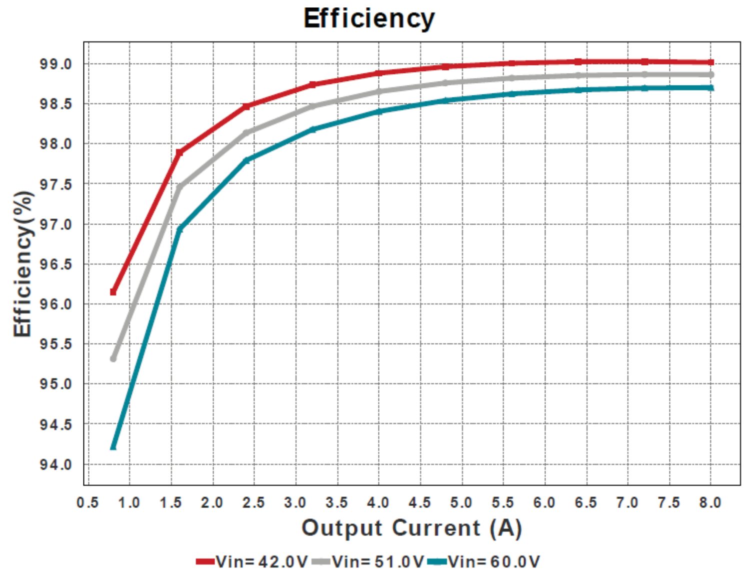
The 300W Low Voltage DC Buck Converter

Below is an example buck converter with a 42 to 60VDC input and a 40VDC/8Amp/300W output.



According to TI's design report, the BOM parts cost is $7.58 and the efficiency is 98.7%. The 1.3% power loss means that 3.9W (300W * 1.3%) is pumped into electronic components and converted to heat, which requires minimal heat sink hardware.

27uF of capacitance and 15uH of inductance can be implemented with multiple L's and C's that are ≤ 7mm tall (~0.25") and cost a total of ~$6.

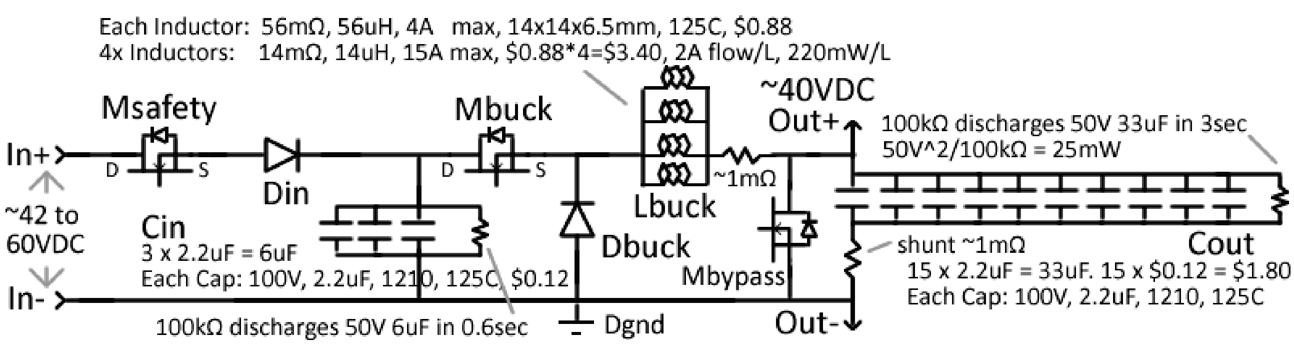


Buck converters have an output voltage less than the input voltage and are most efficient when the output voltage is close to the input voltage. TI's design report shows efficiency as a function of output current and input voltage, which stays above 97% in most cases.

For more information on buck converters, see Wikipedia or Professor Kat Kim's excellent Video.

300W Buck Converter L's and C's cost ~$6 total and are ≤ 7mm tall

We combine multiple L's and C's to implement the classic buck converter, as shown below.



Electrolytic capacitors easily fail and are therefore ultimately expense. Alternatively, if one works with 100V chip capacitors, they could get 33µF for $1.80 total (e.g. 15 capacitors where each is 2.2µF, 100V, $0.12, 1210, 3mm tall, #1276-CL32B225KCJSNNF). Or, if one works with 250V chip capacitors, they could get 10µF total for $3.40 (e.g. 10 capacitors where each is 1µF, 250V, $0.34, 1825, 2mm tall, #1825PC105).

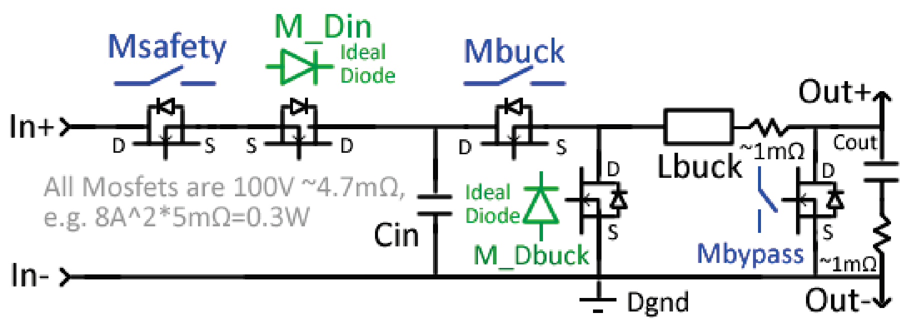
An example Inductor is the #HCM1A1307V2-560-R ($0.85, 56µH 0.056Ω, 4A, 6.5mm tall). If one pumps 8A through four of these in parallel (56uH/4 = 14uH total, $0.85*4=$3.40 total), then 220mW is burned in each (2A^2*0.056). Alternatively, one might combine four #CDEP147NP-4R5MC in series at similar performance and cost. For details, see "~15uH, ~20A, 15mΩ" in this file.

In the above circuit, we place 100KΩ 1206 1% resistors across the capacitors to discharge them in the event the system powers off, for safety. One might utilize two 50KΩ 1206 resistors in series to help support higher voltages. 100KΩ causes 33uF to discharge in 3 seconds. Also, it burns 25mW (50V^2/100KΩ) continuously, which is small compared to our total 300W output. One might increase these resistors (e.g. 5-fold) if they wanted to reduce power loss at the expense of a little safety.

Low Ron MOSFETS Burn Little Power

In the below illustration with have three MOSFETs set up as switches in **blue** color (e.g. $0.63, 5mΩ, 100V, 92A, DPAK, #TPH4R10ANL). If one pumps 8A through 5mΩ, then 320mW is burned (8^2*0.005), which is not terrific, yet is also not terrible. If one wanted to reduce this, they might place two in parallel (and double the cost) or utilize a 2.5mΩ part (e.g. $1.11 GWI Arrow price, 2.5mΩ, 100V, 160A, D2PAK, #TK160F10N1L,LQ).

Shown below in **green** color are two diodes that one might implement as "ideal diodes" via MOSFETS. If one utilizes five 5mΩ MOSFETS total, and they cost $.63 each, then total MOSFET cost would be $3.15.



Mbuck, shown above, is your classic buck converter switch.

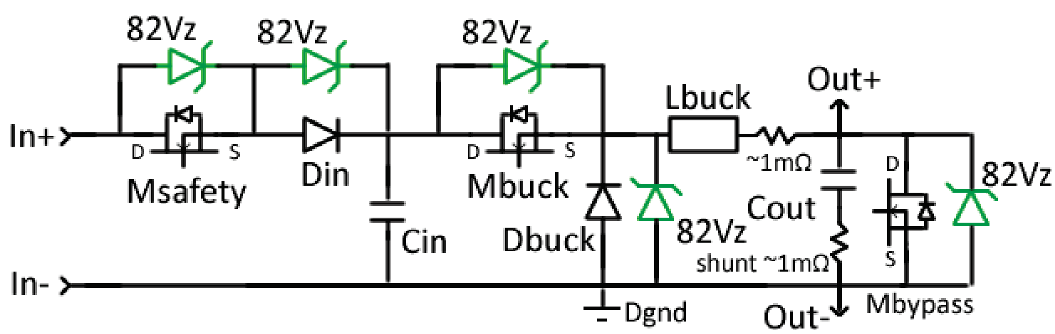
Msafety disconnects the PV panel from the circuit in the event of a fault (i.e. a safety feature). This is open upon power up and therefore stays open if the microprocessor does not boot.

The M_Din ideal diode insures current flows in the correct direction and M_Dbuck is your classic buck converter backflow diode (which can also be used to reduce output voltage). Both are implement as ideal diodes via a MOSFET, to reduce power loss.

The Mbypass MOSFET allows us to bypass the entire circuit in the event it is not functioning properly. This is engaged when the microprocessor is in reset; therefore, the power string can still function if a microprocessor does not boot (i.e. it is replaced with 5mΩ).

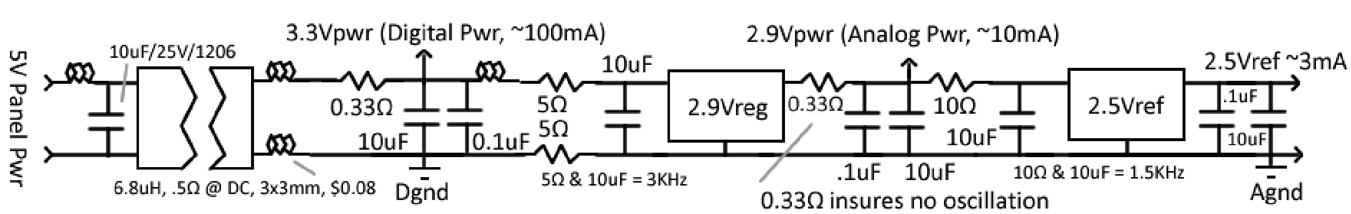
If one is bypassing a converter, they still need to produce the target string voltage (e.g. 400V). If PV solar panels are producing 45V, for example, and one has a string of eight 300W converters, then the string can still function with seven converters (45V * 7 = 315V). However, if two 300W converters failed, one would need to move to the right of the maximum power point and run the solar PV panels at a non-optimal voltage (e.g. ~50V solar panel voltage, 400V/8 = 50V).

All components are rated for 100V; therefore, to reduce risk of damage, we place 82V zener diodes at key positions, as shown below (e.g. $0.10, DO-214AA SMB, #1SMB5947-M4G). If a zener turns on at 82V, and one drives 100mA through it, for example, the zener would dissipate 8W and burn up (82V*0.1A). Therefore, if it does turn on, we would prefer it be on for only a short duration, or it pass only a small current.



Power Supply and Voltage Reference

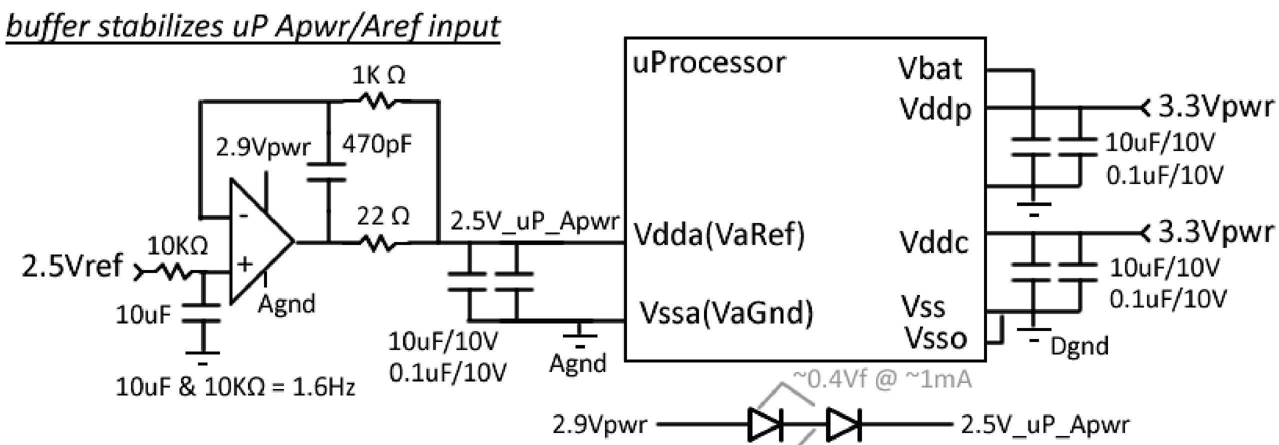
Large panels (e.g. 2x10m, 4kW) contain a local power bus which powers 300W converter pcb's via an isolated VDC-to-3.3VDC power supply module (e.g. #PDSE1-S5-S3-S, 1W, 5Vin, 3.3Vout, $1.56 GWI from Arrow), as shown below. Alternatively, one might build their own module with a small transformer and IC (e.g. #TPS55010). One might work with a low local power bus voltage, such as 5V, if they wanted to utilize low voltage low cost components. Or a higher voltage, such as 48V, if they wanted to reduce the voltage drop along power wires.



In the above circuit, 3.3V powers digital circuits (~100mA), 2.9V powers analog circuits (low noise, ~10mA) and 2.5Vref (2mA) establishes an accurate voltage to facilitate measurements. The voltage reference IC influences system accuracy (e.g. $0.99, voltage reference, 8ppm/°C, 0.1% initial accuracy, >2.8Vin, #MAX6070BAUT25). To improve accuracy and reduce cost, one might measure the voltage reference voltage at the factory (along with other parameters) and store the measured initial accuracy in eeprom. Four inductors further filter high frequency switching noise (e.g. 5uH, $0.08, 3x3mm, 0.5Ω at DC, #NRH2410T6R8MN).

Microprocessor Analog Power, Analog Reference, and Digital Power

An Xmc4xxx microprocessor digital circuitry is powered with 3.3V (digital power), whereas the Xmc4xxx analog circuitry is powered with less voltage, as shown below (i.e. 2.5V into V_{dda} analog power and analog reference input). We buffer the 2.5V reference with an op amp since load changes at the V_{dda} pin will destabilize the voltage reference signal if driven directly. One must pay attention to analog reference buffering in order to maintain accuracy, as we do here.

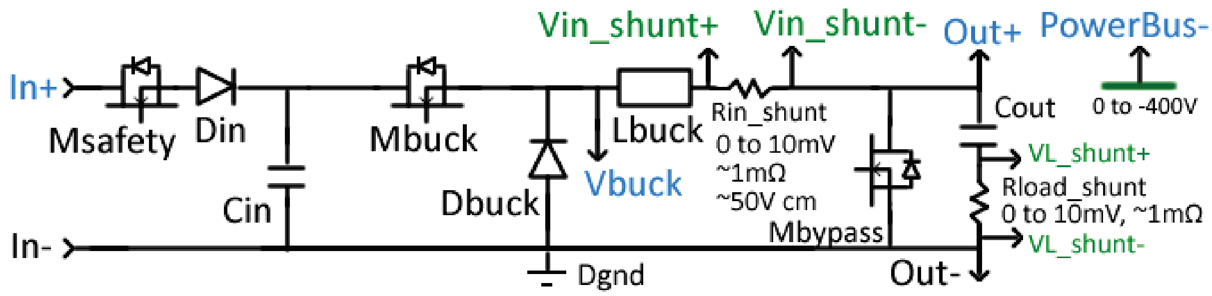


If 2.5V uP Analog Pwr goes down, we don't want op amps to over drive uProcessor Vin pins (e.g. by 5mA, 1V)

Notice in the above lower right corner we have two series Schottky diodes between 2.9Vpwr and microprocessor V_{dda} (2.5V). These insure that the 2.9V powered op amps do not over-drive the microprocessor voltage measurement input pins in the event V_{dda} fails to appear. These two diodes (e.g. 0.4V_f at 1mA) insure op amp power will always be less than 1V more than microprocessor analog power (V_{dda}), which is required by Xmc4xxx processors.

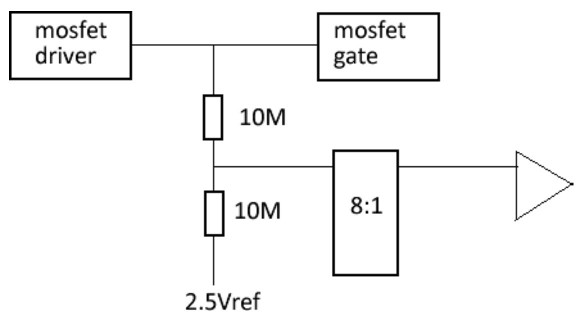
Important Voltages and Currents are measured

Two currents (green) and four voltage nodes (blue) are monitored, as illustrated below.



Measuring currents involves measuring the voltage across a shunt resistor (e.g. 1mΩ, $0.12, 1% initial accuracy, 50ppm/°C, 3Watt max, 2512 package, #CSRL3-0R001F8). This voltage might be small, therefore one needs a high gain-bandwidth amplifier to support a high bandwidth. The Source impedance is low, therefore op amp input pin bias current and capacitance does not affect performance. A 1mΩ shunt would dissipate 64mW with 8A of current (e.g. 8A^2*1mΩ = 64mW). The Rload shunt might be 0 to 10mV, relative to GND, and is therefore easily conditioned with a non-inverting op amp. The Rin shunt is more complicated since it might be at 75V, requiring a $1 high-side current shunt amplifier (e.g. #INA290A4-Q1)

Managing Component Degradation via Standardized Built-in Field Testing

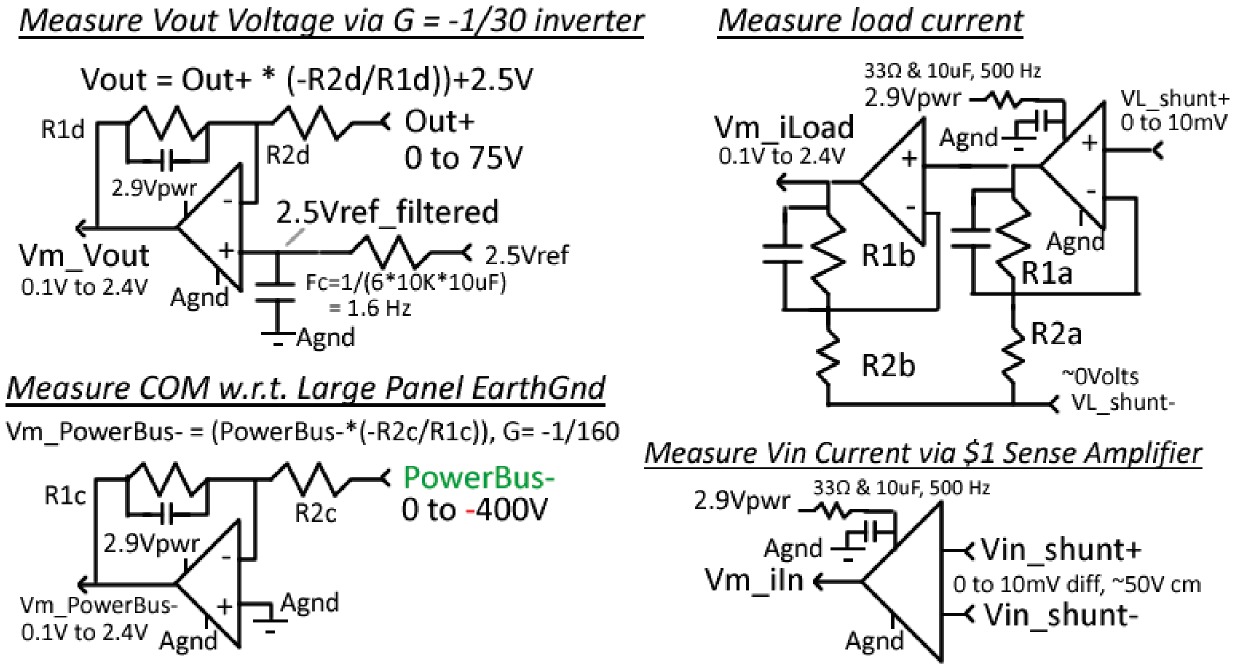


Multiple voltages and currents are monitored on each 300W converter enabling one to measure Cin, Cout, L, MOSFET Ron, MOSFET Gate Leakage, and PV V_{OC}. Researchers propose standard ways of reporting these parameters to a server. Subsequently, customers can measure degradation rates after a reasonable period of time, and not scale to larger volumes until satisfied. Measuring Capacitance and Inductance involves digitizing voltage, digitizing current, and calculating (e.g. i = C * dV/dT). External 48V power enables us to measure things like V_{oc} and MOSFET gate leakage; and CANbus enables us to reliably report all parameters. Shown here is an example circuit that measures MOSFET gate leakage.

Researchers need to reduce noise by a variety of techniques such as averaging multiple DC-to-DC switching cycles and ignoring spikes from inductively coupled switching circuits. One challenge is measuring components with enough accuracy to be helpful at predicting decay rates. Properties vary with temperature; therefore, temperature needs to be kept constant when comparing.

Signal Conditioning Circuits Prepare Voltages and Currents for Measurement

Several signal conditioning circuits are shown below.



Measuring 5 to 75V via an Inverting Op Amp

Measuring a 5 to 75V voltage node (e.g. In+, Out+, Vbuck) requires voltage reduction (e.g. via an amplifier with G = ~1/30 = 6.6KΩ / 200KΩ) since the microprocessor A/D voltage input supports a 0 to 2.5V range. One can do this via an op amp non-inverting amplifier if they are looking for high bandwidth; or a voltage divider if bandwidth is less important. The non-inverting amplifier input pin voltage is stationary, and therefore its input pin capacitance does not form a 1-pole low pass filter with the high input resistor (which occurs with a voltage divider). If one used a 10MHz GBP op amp with G = -1/30 (upper left corner in above illustration), the system bandwidth would be ~10MHz (bandwidth is approximately same as GBP when |Gain| < 1.0). Alternatively, if one used a voltage divider with a 200KΩ input resistor and a 10pF pin capacitance (e.g. typical mux), they would incur a 80KHz low pass filter (1/(6*200e3*10e-12)). In the circuit above, a 2.5V offset is add to the input voltage multiplied by -1/30, which gets us a 0 to 2.5V output given a 5 to 75V input.

If one works with a 10MHz #TLV9061 op amp ($0.22, 25pA input current at 85°C) and a 200KΩ input resistor, for example, they would see a 3uV error due to input bias current, which is ok (25pA * 200KΩ = 3uV, 75V^2/200K = 28mW).

If the op amp drove 2.5V across the 6.6KΩ feedback resistor, one would burn 1mW (2.5V/6.6KΩ = 370uA), which is reasonable.

One would probably want this op amp to be a single (not 2 or 4 amplifiers per package), since crosstalk is higher with a higher source impedance (e.g. with 200KΩ).

Measuring 0 to -400V via Inverting Op Amp

Measuring the 0 to -400V common PowerBus- voltage, with respect to DC-to-DC converter AGND requires an amplifier with a small gain (e.g. G = 1/160). PowerBus- is similar to earth ground and the DC-to-DC converter is floating (e.g. AGND is 0V, 40V, 80V, 160V, 200V, 240V, or 280V w.r.t. earth ground); therefore earth ground is 0 to -400V w.r.t. DC-to-DC converter AGND. If one implemented this with a 5MΩ input resistor and #TLV9061 op amp ($0.22, 10MHz GBP, 25pA input current at 85°C, 8pF input), for example, they would see a 0.1mV bias current error (25pA * 5MΩ = 0.1mV, 400V^2/5MΩ = 32mW) and ~10MHz bandwidth, which is ok. The op amp input capacitance would *not* create a 1-pole RC filter, since the op amp input pin voltage is fixed at ~0V. A 31KΩ feedback resistor would provide G = -1/160 (1/160 = 31K / 5M). For details, see "Measure High Voltage via Voltage Divider" in this file.

Measuring 0 to 10Amp load current

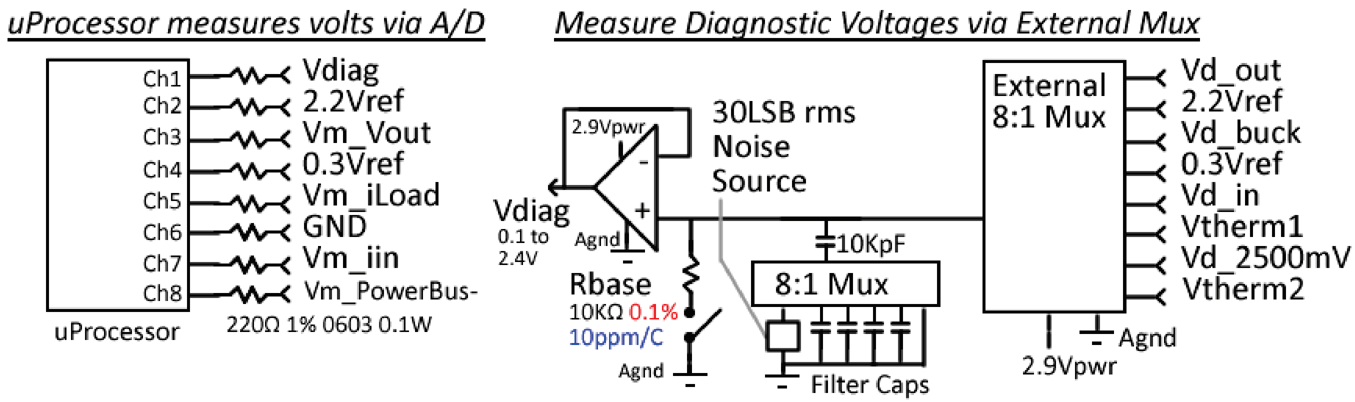
Measuring the load current (e.g. 0 to 10mV across VL_shunt) requires a two stage amplifier since we need high gain to boost it to 0 to 2.5V (G = 250 = 2.5V/10mV). If we have two stages, G=16 per stage, and the op amp GBP is 10MHz (e.g. #TLV9062, dual op amp, $0.22, 10MHz GBW) then the resulting amplifier bandwidth would be ~625KHz (10MHz/16). We filter the power supply with 33Ω and 10uF (500Hz = 1 / (6*33*10e-6)) since we do not want power supply noise to influence our tiny 10mV input.

Gain Accuracy

Since we can measure initial amplifier gain and offset at the factory and store in eeprom (i.e. due to op amp offset voltage and resistor initial accuracy errors), we can work with low cost thin film resistors with a 0.5% initial accuracy error and 25ppm/°C drift. These cost $0.03 for 1206 (0.25W, 150V), $0.01 for 0805 (0.12W, 100V), and $0.01 for 0603 (0.06W, 75V). One might use two 1206 to measure the 75V voltages (e.g. 100Ω * 2 = 200KΩ) and four 1206 to measure 400V (e.g. 1.25MΩ * 4 = 5MΩ), for safety. For ≤ 10V circuits, one might use 0603 resistors when working with ≤ 15mW and 0805 when working with ≤ 50mW. Gain error at 70°C due to temperature drift from the ratio of two resistors is 0.04%, which is ok ((25+25ppm/°C)*(70°C-25°C)).

Microprocessor A/D Measures Multiple Voltages

Many microprocessor include an A/D converter with multiple analog input pins, as shown below at the left.



We utilize an additional external 8:1 multiplexor (e.g. $0.35, 8:1 mux, 5.5Vpwr, 5nA at 85°C, 8pF, #NLAST4051DTR2G) and op amp buffer (e.g. $0.22, 10MHz GBP, 25pA @ 85°C, 8pF, #TLV9061) to further condition inputs. The filter 8:1 mux enables one to add noise or add low pass filtering. This mux could be low cost due to the 10K pF blocking capacitor which eliminates the effect of leakage current (e.g. $0.11, 8:1 mux, 10Vpwr, 400nA at 85°C, 8pF, #74HC4051PW118).

The Rbase SPST enables voltage divider measurement and requires a flat Ron resistance (e.g. $0.12, SPST switch, 5.5Vpwr, 10nA at 85°C, 8pF, #NLAST4501DFT2G). We would want the op amp and the SPST components to be singles (one op amp per IC, one SPST per IC) due to crosstalk vulnerability when working with high source impedance (e.g. 300KΩ).

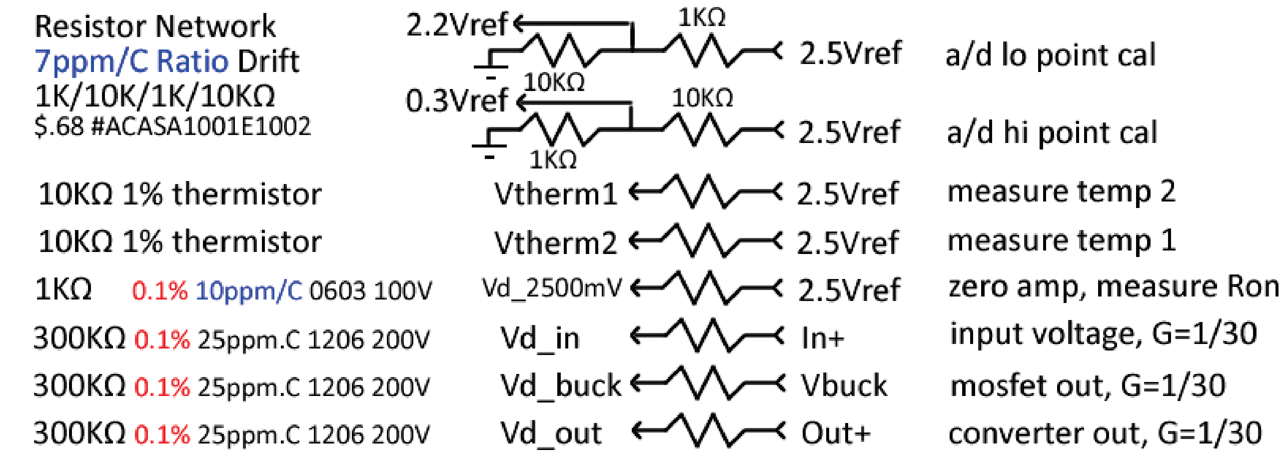
A ~30 LSB_{rms} noise source improves accuracy during calibration by allowing one to measure a source plus noise. One looks at the average value of thousands of measurements. For example, if you add 1V to $0.04V_{rms}$ of noise and average 4K samples, you will see 1.0006V (1.0V + (1/Sqrt(4000))*0.04V). The advantage is you end up utilizing ~100 A/D positions instead of several, each of which might have a ±4LSB differential linearity error. If your calibration point is on a code that is error prone, then you will calibrate with added error. In the end, one might improve accuracy 3 to 9-fold with noise and averaging many samples.

The filter 8:1 mux also allows one to switch in several different filter capacitors, to reduce noise presented to the A/D. This is a little tricky, since one needs to wait a little while for the capacitor to acquire the signal after connecting.

Voltages are prepared for Measurement

Several nodes are prepared for voltage measurement using thin film resistors, as shown below.

Prepare diagnostics Voltages



0.3Vref and 2.2Vref

Two point calibration at 0.3V and 2.2V enables one to calibrate the A/D in the field (since 0V and 2.5V are not reliable due to being too close to the power supply rails). A thin film resistor network with onboard 1KΩ/10KΩ/1KΩ/10KΩ resistors tends to have stable ratios and is therefore helpful at synthesizing 2.2V and 0.3V (e.g. $0.68, resistor network, 1KΩ/10KΩ/1KΩ/10KΩ, 8ppm/°C ratio drift, #ACASA1001E1002P1AT).

In+, Vbuck, Out+

In several cases (i.e. In+, Vbuck, Out+), we measure 5 to 75V via a 31:1 voltage divider (which converts to 0 to 2.5V). Our Rbase (lower resistor in divider) is 10KΩ, therefore we might consider a 300KΩ input resistor (G = 10 / (10+300) = 1/31) that burns 18mW at 75V (75V^2/300KΩ). To encourage accuracy we might look at a very accurate 300KΩ part (e.g. $0.07, 25ppm/°C, 0.1% initial accuracy, 1206, 200V, #RNCF1206BTE300K).

2.5Vref

The 2.5Vref and 1KΩ 0.1% 10ppm/°C series resistor enables us to measure the 8:1 multiplexor Ron plus Rbase SPST Ron resistances (assuming Rbase and 1KΩ are accurately measured at factory and do not change); and also helps us establish a known voltage at filter capacitor in-between switching channels, to reduce channel crosstalk due to memory from the filter capacitor. After determining the voltage divider ratio (Rbase / (Rinput + Rbase)), one can calculate 5 to 75V voltages, and calculate thermistor resistances.

Thermistors

We place two thermistors on the PCB to measure temperature (e.g. 0603 thermistor, 1% resistance accuracy, $0.05, NCU18XH103F60RB). The resistance across a thermistor varies with temperature (e.g. 27KΩ@0°C, 10KΩ@25°C, 2KΩ@70°C). If the resistance varies 3% for each degree C, then 1% resistance accuracy translates to ± 0.3°C temperature accuracy, for example. If one wanted more accuracy, they might consider going to a $0.12 part that is twice as accurate (e.g. 0.5% resistance accuracy, $0.12, #NCU18XH103D60RB). If one has several accurate thermistors on the PCB, they can more easily look for fire and components burning especially hot. One could also set up thermistors with their own op amps and comparators to create a real-time alarm signal that does not require the a/d and the microprocessor (e.g. better fire detection).

Sources of Measurement Error

Voltage Divider Base Resistor (Rbase)

Several sources (e.g. 50V node, thermistor) are measured via a voltage divider where Rbase (e.g. 10KΩ) forms the 2nd resistor attached to AGND. Rbase with 10ppm/°C temperature drift insures reasonable stability over temperature (e.g. 0.1%, 0603, 10ppm/°C, $0.15, moisture resistant, #RT0603BRB0710KL). For additional accuracy, one might accurately measure Rbase's initial value at factory and store in eeprom.

Resistor Temperature Drift

If one is operating at 70°C and is dependent on the ratio of the 0.3Vref/2.2Vref resistors, they might see a 0.05% gain error ((8ppm/°C ratio drift) * (70°C-25°C)). If we add in the temperature drift from an 8ppm/°C voltage reference IC, we would see an *additional* gain error of 0.04% (8ppm*(70°C-25°C)); yielding a total gain error of 0.09% (i.e. one part in 1100 at 70°C), which is reasonable considering we are working with low cost parts.

If one is doing 5 to 75V measurement at 70°C, for example, then the 300KΩ resistor temperature drift might add an additional 0.11% gain error ((25ppm/°C * (70°C-25°C)).

Current Shunt Resistor Initial Accuracy

Current shunt resistors typically have an initial accuracy of 1%, therefore one must measure at factory and store in eeprom if they want higher accuracy. After calibrating out initial accuracy, one is often limited by temperature drift. For example, the error at 70°C with a 75ppm/°C resistor is 0.33% (75ppm/°C * (70°C-25°C)).

Input Bias Current Error

The input bias current of the buffer op amp (25pA @ 85°C) and signal selection 8:1 mux (5nA @ 85°C) forms an error with the 300KΩ input resistor. The Filter 8:1 mux leakage current has no effect due to the 10KpF blocking capacitor. The Rbase SPST leakage current also has no effect since this current is pushed through both resistors and therefore does not change the voltage ratio. The mux 5nA gives us a 1.5mV error @ 85°C (5nA * 300KΩ), which is one part in 1600 (1.5mV / 2.5V). However, leakage current decreases by a factor of 2 every 6°C, and by a factor of 4 every 12°C. Therefore, one would see a 1 out of 6400 error (1600*4) at 72°C (85°C - 12°C).

Bandwidth Limited by Pin Capacitance

The pin capacitances from the signal selection 8:1 mux, filter 8:1 mux, and op amp input; summed together; form a 1-pole RC filter with the source impedance (e.g. 300KΩ when measuring 5 to 75V). Subsequently, one might see a bandwidth of 22 KHz when measuring 5 to 75V sources (F_c = 22 KHz = 1 / (6.2 * 300e3 * (8+8+8)*1e-12) = 1 / (2*π*R*C)).

Setting up the Array

The master controller maximizes the output of the entire system via the following process:

1. Calculate the MPPT point for each 300W circuit based on its solar I/V curve (i.e. calculate Voltage into 300W Converter, Current into Converter, Power into Converter).
2. Calculate the proportion of total power for each converter. For example, if you have a string of 3 converters with solar MPPT of 100W, 150W and 200W (450W total); then portions of total would be 22%, 33%, 44% respectively (100/450, 150/450, 200/450).
3. Divide total power by target string voltage to determine target string current (e.g. given 100 Volt target string voltage, target string current would be 4.5A = 450W / 100Volts).
4. Set 300W converter Voltage Outputs proportional to their power outputs (e.g. 22%*100=22V, 33%*100=33V, 44%*100=44V).

One can check the numbers to see that the common current (e.g. 4.5A) multiplied by converter output voltages matches MPPT powers (e.g. 4.5A*22V=100W, 4.5A*33V=150W, 4.5A*44V=200W). Also, one can check that the sum of the converter output voltages match the target string voltage (e.g. 22V+33V+44V=100V).

If working with multiple strings in parallel, one needs their total string voltages to be the same (i.e. "balance"). Subsequently, given N converters in a string, one might set up one to limit current and the others to limit voltage. For example, converter #1 limits at 22V and 5A (higher than 4.5A), converter #2 limits at 33V and 5A (higher than 4.5A), and converter #3 limits at 46V (higher than 44V and not achieved since current limiter kicks in first) and 4.5A (we hit this limit since it matches total load).

Load Management

The system load might change suddenly. Subsequently, the master controller needs to be able to quickly broadcast a CANbus message to all converters requesting an adjustment (e.g. same 8 byte message sent to all processors at one time). Perhaps the message also includes rate information (e.g. gradually move from I/V point #1 to I/V point #2 over X µSec).

The master controller, which is physically located in the off-panel box of electronics, is a critically important element since it coordinates all converters. It must continuously monitor system load and act accordingly. Getting this to work, reliably and efficiently, poses a nice challenge to researchers.

Fault Tolerance

Let's assume we have a very large solar panel (e.g. 2 x 50 meters, 20kW, 300W per converter, 65 converters) and we want this to last without too much degradation for 30 years. Also, let's assume some of the pieces are going to fail. And when they do, we do not want a system-wide failure, only minor degradation. Below are several things one might do to promote fault tolerance:

- If a converter's processor does not boot, a bypass MOSFET across output engages and allows string to continue passing current.
- If a converter's power supply (e.g. 3.3V, 6.6V) does not appear, the next converter in the string sees this and pulls up bypass MOSFET gate to turn it on.
- If converter's communication with master controller is down, then its bypass MOSFET engages and string continues to pass current.

At some level of fault, a system wide failure does occur. What would it take?

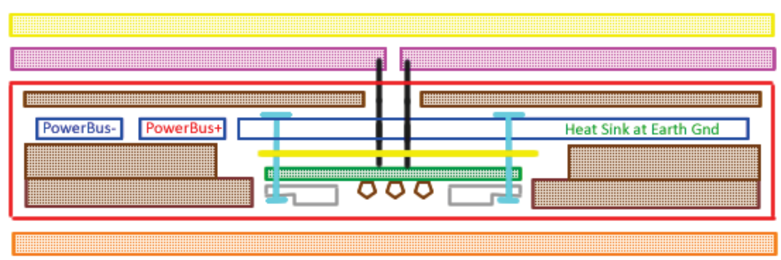
- Failure of Common Power Bus (e.g. 400VDC), common Local Power (e.g. 5V for processors), or common CANbus (e.g. CANbus Hi/Lo).
- Master Controller failure.
- Local Power Supply failure.
- Master Controller loses communication with array of 300W converters.

How to mitigate the above items?

- Master Controller PCB and Local Power Supply are external units that could be replaced.
- If the 300W elements are buck converters (i.e. Vout < Vin), then one might not be able to produce the target string voltage if too many converters go down. Subsequently, one might prefer a buck-boost design, which can also create Vout voltages greater than Vin (at increased cost).

- A failure (e.g. open or short) along common bus wires (local power, CANbus, HiPwrOn) would be bad. To mitigate, one might:
    - Not break common bus wires and instead remove plastic insulation and attach to connectors or solder directly to PCB. For example, the top two wires in the "T tap" connector at the right are not internally broken.

    - Place four 300W converters onto one PCB, to reduce the number of connectors to common bus wires.
    - Employ heavier common bus wires and/or heavier insulation
    - Utilize two wires in parallel for each signal, so that if one breaks, the other can continue to function. This applies to connectors as well -- two connector pins for each signal. The GW Instruments [i4xx] product has a 50 pin backplane connector with two pins per signal and has never seen a backplane connector problem in 10 years of production.
    - Previously we looked at using PowerBus+- sheet metal as a heat sink. However, if the insulation between a component and PowerBus fails (e.g. thermal pad burns up), then the PowerBus would go down and we would get a system wide failure. Subsequently, one might utilize three plates: two for PowerBus+-, and one for thermal heat sink and mechanical strength (possibly tied to earth ground), as shown above. The yellow pad next to the PCB in the above illustration conducts thermally yet not electrically (for examples of this, click here).



      There are different ways to do this. One is to mount parts on PCB and use thermal vias to transfer heat to PCB surface that presses against metal plate (or 0.01" away via buried vias to solid FR4 layer). Another is to attach TO-220 directly to metal plate via thermal pad.

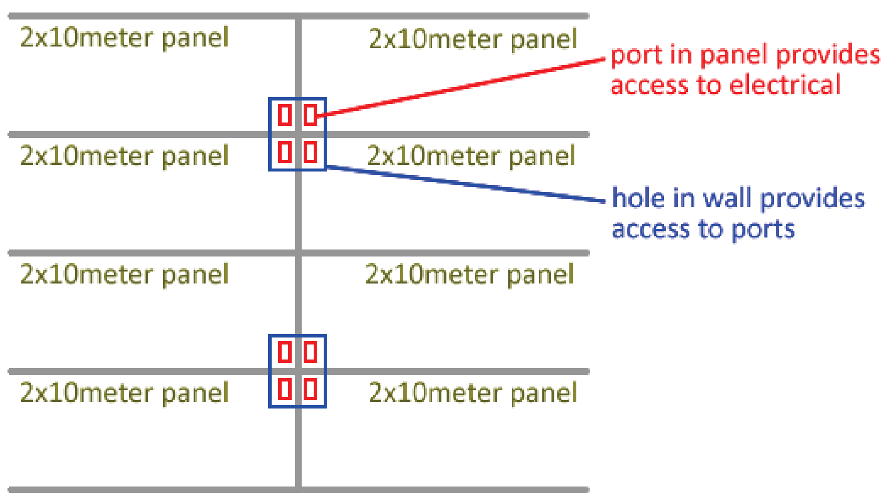
      Notice that our parts might be 400Volts with respect to earth ground, therefore one needs to electrically isolate via a thermal interface. However, if the insulation fails, we do not get a system wide failure if we are shorting to earth ground (and subsequently turning off the associated 300W element).

Corrugated Steel Commercial Roof (Ap3)

Corrugated steels panels with built in solar are mounted on commercial building metal framing via crane, as pictured to the right. Panels are mass produced in a factory, to reduce parts and labor costs. Panels stack on back of flatbed truck or inside shipping container during transportation. Corrugated steel roof is a traditional practice with commercial buildings. We look at integrating solar PV and electronics into these panels at the factory, and having them interconnect, plug and play.

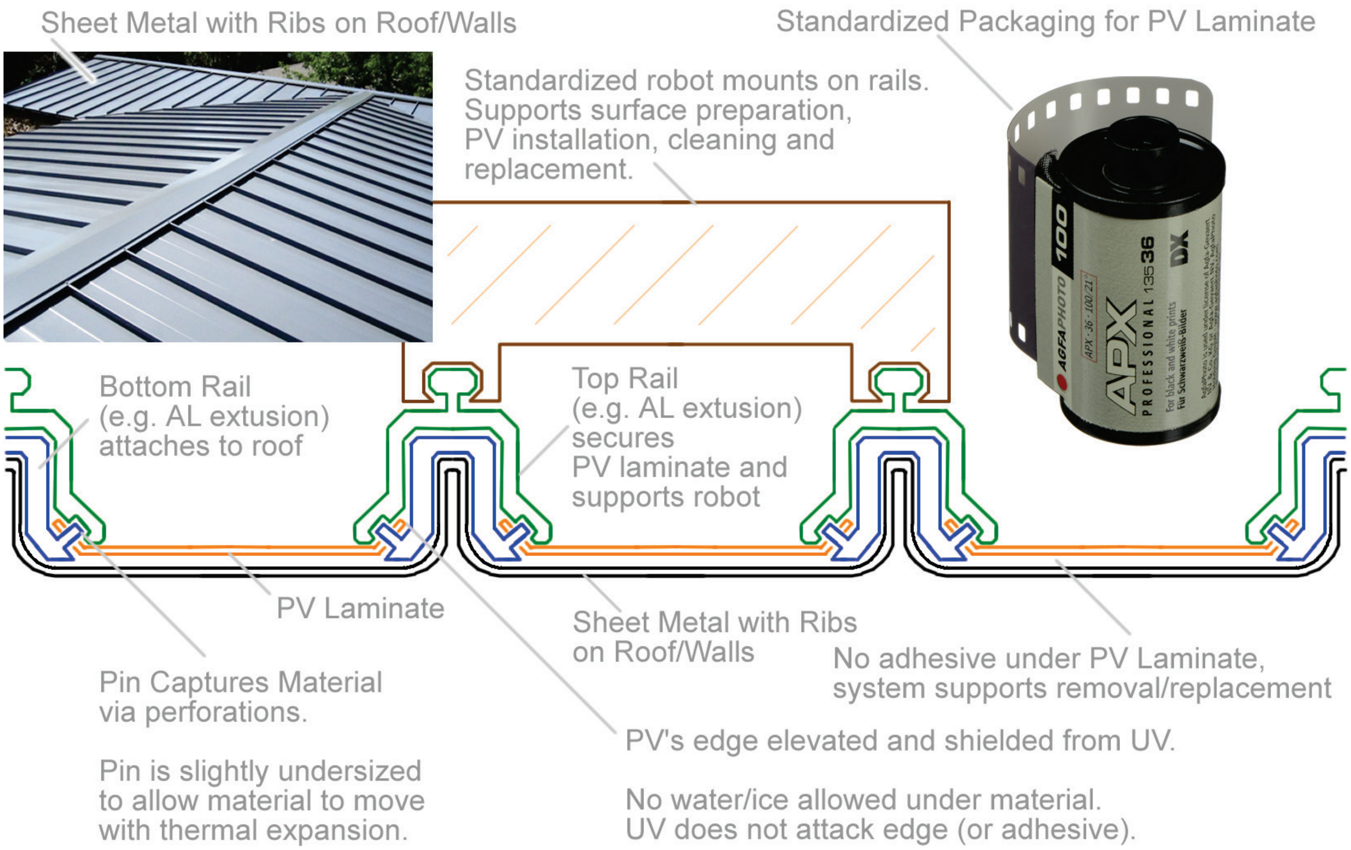
In the above picture, panels control rain water using overlapping metal joints.

The illustration below is an example of how large panels in an array might be attached to the surface of a commercial building. Power enters building via physical ports (holes) on a 4 meter x 20 meter matrix. This is just one concept. There are many other ways of routing power.



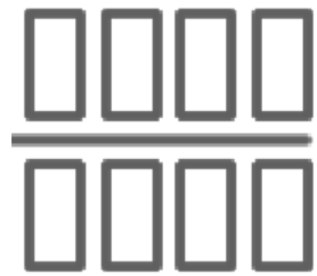
Rolled Material to Metal Ribbed Roof (Ap4)

At this time, there exists products that involve rolled solar material to metal roof via adhesive. However, UV attacks adhesive at edges, and metal is deformed upon removal of solar material (metal plate bends when adhesive does not release). The below illustration (not shown to scale) shows how one might fix these problems. Mono-silicon and poly-silicon have a large minimum bend radius, therefore other solar PV products might be better suited for this application.



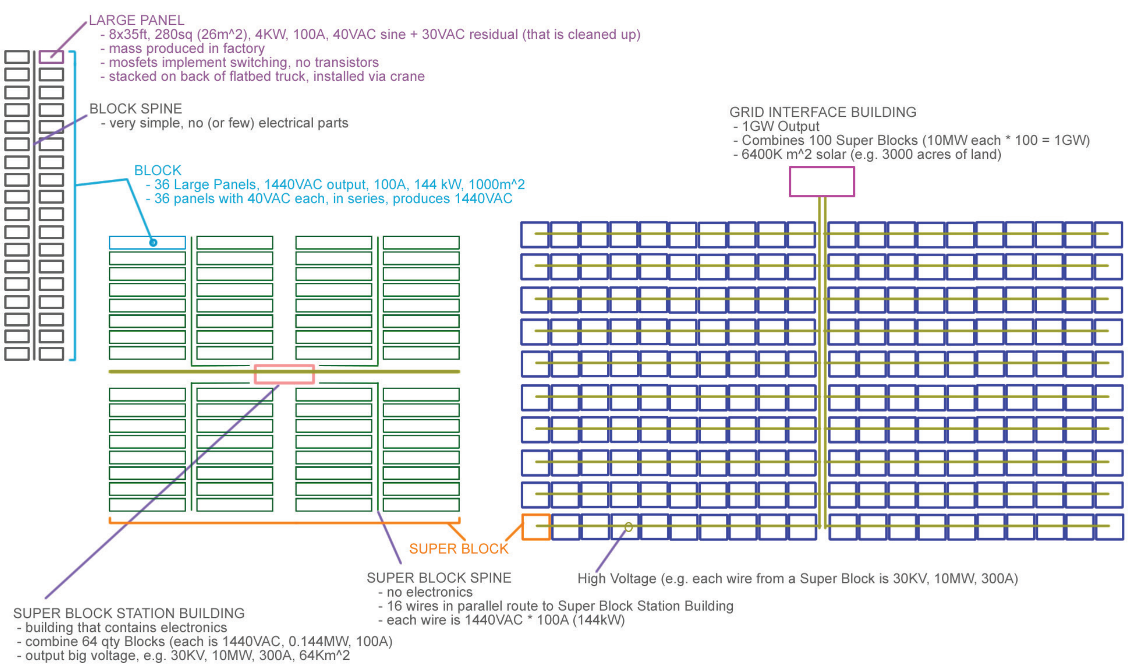
Elevated Solar On Land (Ap5)

Similar to the above yet corrugated solar panels are mounted on metal framing, on land, and connected together along a spine.



The below illustration shows how 250,000 of these panels might be configured to produce a 1GWatt solar farm. This might seem like a lot of panels, and it is, yet if system cost is $1.50/Watt ($1.50B for 1 GW), for example, and half the budget is for panels and the other half is everything else, then one might budget $3K per panel, parts and panel factory assembly labor (50% of $1.5B is $0.75B, 0.75B/0.25M = $3K). The illustration to the right shows how eight 2 x 10meter panels might be configured along a central spine.

Typical cost of solar PV silicon material is [$0.20/Watt]($820 for 4KW), typical cost of 460LBs of raw steel is $230 (2m x 10m x 3cm, top/bottom/wavy sheets all 0.3mm thick, $0.50/Lbs., 2 * 10 * (0.0003 + 0.0003 + (0.0003*2.5)) * 7850 * 2.2 * 0.50), and cost of thirteen 300W networked DC-to-DC converters (300VDC/13A panel output) is estimated at $520 ($40 * 13 = $520). These are your primary components, and they would total to $1570 using this rough estimate ($820 + $230 + $520). Consequently, $3k total panel cost is within the range of possibilities. Obviously, solar farm design and cost modeling deserves more careful study.



Chapter 8) Design Considerations

Goals

Reduce fossil fuel use, reduce energy consumption, increase comfort, and reduce cost.

Features

- Supports large rolled flexible panels (e.g. 2 meters in diameter when rolled and 2 x 50 meters when flat). These can be cut into smaller pieces and placed onto buildings and directly onto soil, on land.
- Supports large ridge flat panels (e.g. 2 x 10 meter stacked on back of flatbed truck).
- Supports multiple layers (i.e. lamination) with metal conductors and embedded electronics (e.g. multiple PCB's).
- Supports different solar PV technologies (e.g. mono Si, poly Si, thin-film).
- Provides standardized communication for multiple PCB's embedded in panel (e.g. CANbus).
- Mass produced in factory.
- Supports plug-and-play.
- Supports solar farm, commercial buildings, carport, parking lot, and residential.
- Supports attaching solar directly to roof and to wall.

Challenge for Engineers

Design system that is less cost than traditional system; or if it is higher cost, it must pay for that higher cost with less energy consumption over a reasonable period of time.

System Prototype Test Laboratory

A 2000 square foot house-like test site might test multiple devices within a large home-like system. This structure is being designed by Manhattan 2 Chief Architect John Meyer using Revit software, and is summarized below:

> *Proposed Energy Infrastructure R&D Test Laboratory, 1 Page Summary*
> http://www.ma2.life/doc/plan/Ma2_TestSite_Poster.pdf
>
> *Proposed Energy Infrastructure R&D Test Laboratory, Requirements, 2k sq ft*
> http://www.ma2.life/doc/plan/Energy_Infrastructure_RD_Center_v3.pdf

Multiple Standards

S^3 involves multiple standards, and each deployment uses several. For example, a commercial roof might use a solar corrugated steel mechanical standard, electrical connector standard, one of the internal electrical power configurations, communications protocols for multiple PCB's, and electrical bussing standards within panels.

Manhattan 2 Collaboration System

Researchers can collaborate via the Manhattan 2 Collaboration System, described here:

> Manhattan 2 Research Collaboration System
> http://www.ma2.life/doc/research/common/Ma2_Collaboration_System.pdf

Existing Technology

Our proposed system is similar to solar power optimizers, which do MPPT DC-to-DC conversion on a panel-to-panel basis. Most optimizers work independently and output a fixed DC voltage without coordinating with other optimizers to build a target string high voltage. Yet several systems are set up to communicate via a propriety protocol with a master controller. In these cases, one optimizer might increase its output voltage if its neighbor's output voltage decreases (e.g. due to shading).

An example optimizer-based system is SolarEdge. For details on this, see: Overview, Installation Manual, Communications Guide, Creating Fixed String Voltage.

Proprietary communications protocols have several disadvantages:

- Increases cost since each manufacturer needs to develop their own communication protocol.
- Products from different manufacturers do not talk.
- Replacement parts over a system's lifetime might be difficult to acquire.
- Existing systems communicate via ZigBee or power line, which involves much processing (each optimizer needs to do many arithmetic operations per second to pull signal out of noise while listening) and wireless is not known as being five nine's reliable.

Our proposed system differs from existing systems in the following ways:

- We support combining multiple strings in parallel, which is possible due to our fast and reliable communication system (e.g. CANbus), and our support for both voltage and current limiting (instead of just voltage).
- Our system relies on CANbus, a fast and reliable communication system which provides great reliability and can broadcast a message to all device processors in dozens of microseconds (e.g. to deal with sudden load changes).

- We are working toward standardizing the communications protocols between multiple processors; to reduce costs and reduce risk of difficult-to-locate replacement parts. It is our intent to provide free and open reference designs to all manufacturers, to further reduce cost, to reduce climate change.

Costs of Solar

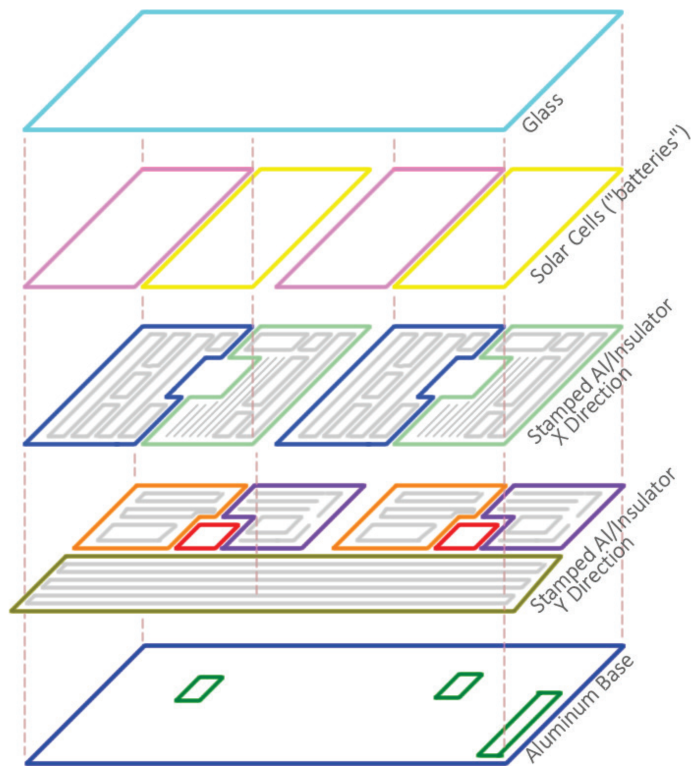
For the cost data on solar projects, please click on the below references:

- U.S. Solar Photovoltaic System Cost Benchmark, NREL, 2018 Report
- Cost of Solar, NREL web portal
- NREL Cost Reduction Roadmap (Jan 2018)

Further Reading

The following chapters within Manhattan 2's Blueprint document contain more ideas on next generation solar technology.

- Page 37, Chapter 3, Mass Produce Smart Solar Material That Includes Switches/Processor
- Page 43, Chapter 4, Automate Installation of Solar Direct to Plywood Roof & Walls
- Page 49, Chapter 5, Automate Installation of Solar onto Corrugated Steel Panels & Frames



Chapter 9) Issues that Require Further Consideration

The following issues require attention.

Heat from Sun

Embedded electronics need to survive typical solar panel temperatures. If ambient (outside air) is 120°F (49°C) and panel heats up to 1.4 times ambient (due to sun heating surface), then panel will heat to 68°C (154°F, 49°C*1.4). If electronics add another 15°C, then electronics will go to 83°C. Xmc1404 processor, for example, operates at -40°C to +85°C.

Heat Dissipation from Electronics

If roof has insulation pressed against panels from underneath, then heat might need to escape via solar panel top surface (heat transfer out bottom surface blocked by insulation). Heat flow from embedded electronics needs careful consideration. If one spreads out heat over a large surface area, then heat management is easier. If a 300W buck converter is 98% efficient, then 6W might be dissipated from a 10x10cm PCB every 1.5m^2 of solar material, which is manageable.

Electrolytic Capacitors

One needs to keep electrolytic caps cool, else they burn out (e.g. many are rated to run 1000 hours at 105°C). One should avoid electrolytic caps if possible, especially with electronics embedded inside difficult to access places, such as solar material. A 300W buck converter could be implemented with 18 chip capacitors (each 2.2uF, 1210, $0.12, 100V), for example.

Mean Time between Failures

Electronics embedded in panels is difficult to service; therefore, we need to be tolerant of faults within cells and electronics. An example approach is switches that bypass not working or underperforming elements. Another technique is to spread out electronics to reduce temperature, to increase component lifetimes.

High Voltage Standoff Distances

On needs to provide distance and insulation to support higher voltage levels.

Fire Safety

If a panel is positioned close to a flammable material (e.g. plywood), one must reduce threat of fire by a variety of techniques:

- Offset solar from wood via corrugated metal (e.g. 1" to 2")
- Ground fault projection (e.g. aluminum foil around conductors and electronics looks for voltage drop due to electronics that broke through to that layer, and turns off system if detected).
- Temperature sensors (i.e. looks for high heat fault).
- Solar material every X Watts includes an on/off switch that stops current flow. If X is 300Watts, for example, then one can limit power fault to that amount (e.g. fault occurs before switch and dumps 300W of heat into one location).
- Thermal insulation layer between power and plywood (e.g. stops 300W of heat at one position from heating plywood to 300°C)
- HiPwrOn wire is pulled high to 3.3V via 10KΩ resistor to indicate panel is healthy, and anyone can pull low to cause all switches to open.

Fire Fault Switch

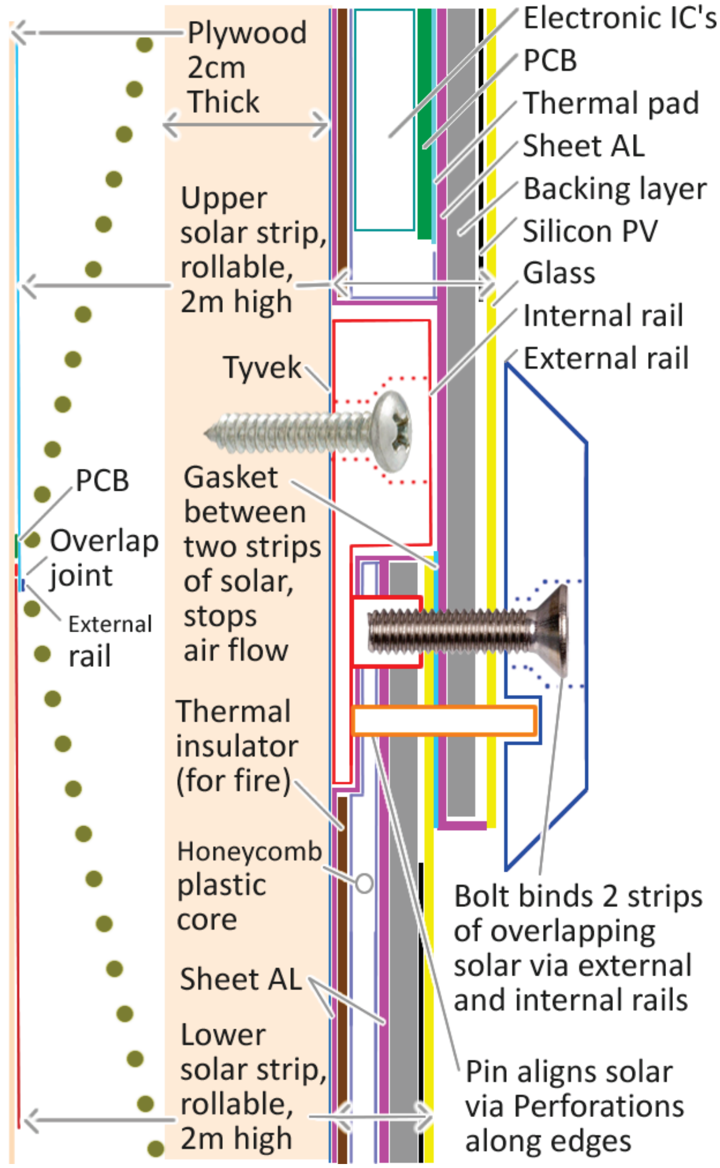
One can have fire prevention switches every *X* Watts (e.g. 100W) which opens in the event of fault. This could be smaller than the converter electronics (e.g. 300W converter coupled with three 100W fault switches). *X* might be a function of thermal insulation between flammable plywood and electrified material. The more thermal insulation, the larger the *X*. More insulation involves more cost. One can develop cost models for electronics and thermal insulation, for different values of *X* and different insulation materials and thicknesses.

Ground Fault Protection -- Aluminum Foil Layer

One could have a thin layer of sheet aluminum foil tied to earth ground, to facilitate a Ground Fault Protection system. One would measure voltages across this foil and look for current. If one finds it, then that means something broke through the above layers and is conducting electricity. In this event, the entire system initiates an Emergency Shut Down.

Overlapping Joints

The illustration to the right shows how one might attach overlapping strips of solar direct to plywood wall or roof. Each strip is 2meters (6ft) high. The left Illustration side of this illustration shows a 12ft x 1.5inch view, whereas the right side of this illustration expands at an overlap between two solar strips and shows a 5inch high x 2 inch wide view.



For more ideas on how to connect solar direct to building surfaces, see Manhattan 2 Blueprint Chapters 3, 4 and 5.

Resistance to Hail Stones

Mechanical engineers support resistance to hail (e.g. 1" hailstone at 52 mph) via mechanical modeling and testing.

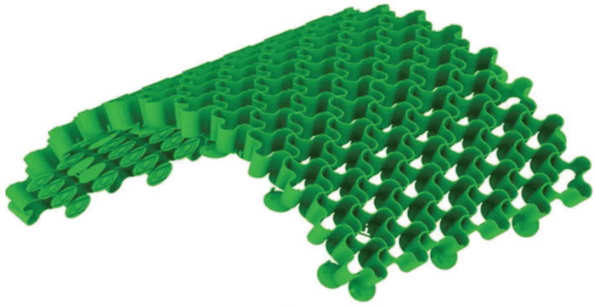
Resistance to Wind, Rain and UV

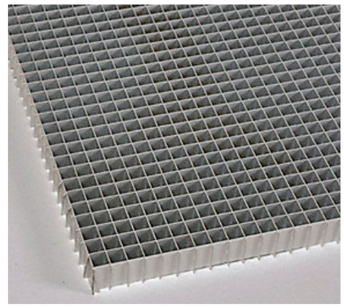
Mechanical engineers support resistance to thermal cycling, wind, rain and UV via mechanical modeling and testing. Simulator can blast with 50 years of wear-and-tear and look at result.

Controlling Wind in LiPV Applications

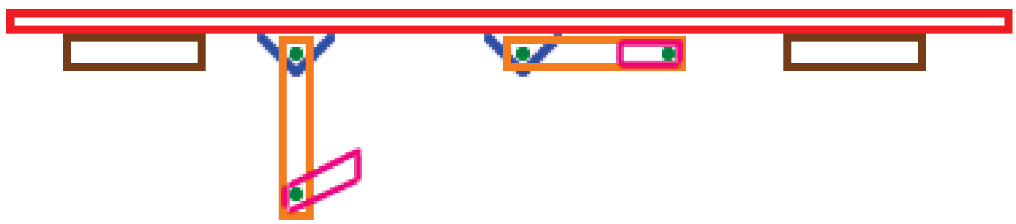
What can one do to reduce wind? Add berms with bulldozer (e.g. Saudi and Iraqi border, 1993)? Add chain link fence with embedded windbreak material?

What can one do to increase rigidity? Add plastic internal honeycomb material?





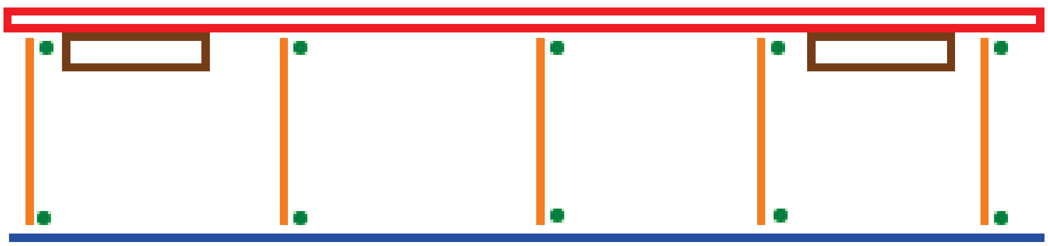
Researchers study different anchoring techniques for Land Integrated solar material, an example of which is shown below. In this illustration, the ~2mm thick solar material is red, ~300W ~1cm tall electronics spaced every ~1.5m^2 are brown, ~15cm long mechanical arms that anchor into soil are orange, and hooks that affix into soil are fuschia. The anchor on the left is deployed, whereas the one on the right is still in the folded position (before deployment, still rolled). If anchors are on a 20cm matrix, for example, then the installation machine might cut trenches 20cm apart, and pack soil into trench after anchors unfold.



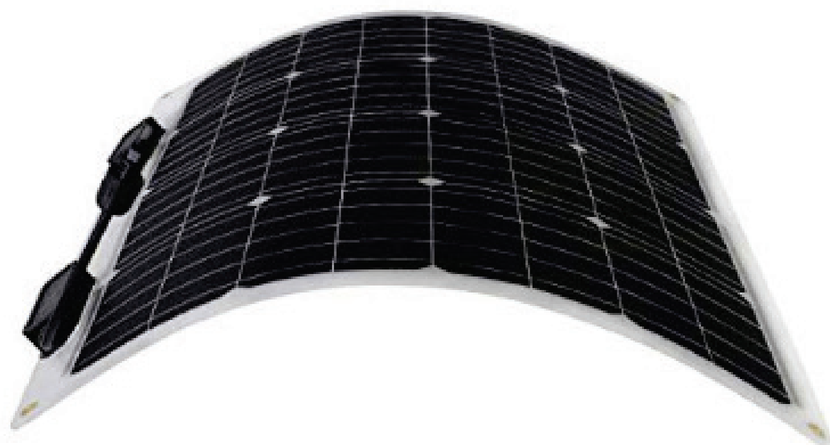
Anchors could take any shape. In the above illustration, we have arms, yet an alternative would be a ~15cm x ~50cm surface with features at bottom that unfold and drop into trench. Anchors could be made of plastic or metal. In some cases, material bottom surface is not flat and requires installation machinery to press lower protrusions into soil, which is ok

Metal strapping over material that is staked to the ground could be used to hold it into place; however, wind buffeting (back and forth) might pull at those stakes.

Researchers also consider two layers: (1) an upper layer on soil surface and, (2) an anchoring submerged layer ~15cm below surface. An example of this is shown below. The upper ~2mm thick solar material is red, ~300W ~1cm tall electronics spaced every ~1.5m^2 are brown, ~15cm long mechanical links (e.g. zinc coated steel wire) that connect the two layers are orange, and bottom anchoring layer is blue. The bottom layer could be plastic or metal (e.g. zinc coated hardware cloth steel mesh on 1cm matrix, shown at lower-right).



Researchers can also test prototypes via existing 3mm thick flexible solar panels, with or without electrification. These could be placed in a harsh and windy area, secured to land by different methods, and observed for changes.

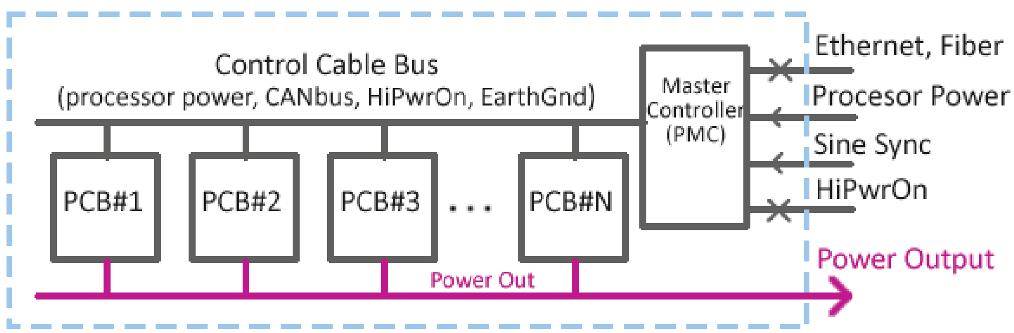


Water and NEMA Rating

System must be resilient to water and condensation.

Panel Master Controller

Internal PCB's connect to Master Controller PCB via a daisy chained bus. Master Controller talks to local area network via traditional means (e.g. Ethernet fiber, Wi-Fi, CANbus).



Standardized Solar System, e.g. 2 x 10meters, includes embedded conductors and electronics

CANbus is built into many processors and has been established by the automobile industry as being reliable. Also, if a processor is isolated (e.g. processor COM is 100V with respect to Earth Ground), then a $2 isolated CANbus transceiver (e.g. #ADM3050e or #ISO1042) enables one to communicate w/ that processor.

Standardized Internal Bus

Embedded PCB's communicate with each other via a standardized internal cable that includes something like: power for processors, CANbus, emergency shut down signal ("HiPwrOn"), and sine wave for synchronization (e.g. sync to grid 60Hz).

$3 Microprocessors

The XMC4200F64K256 processor is $3.30 and supports both serial interface to CANbus and the driving of a power converter (e.g. 48VDC to 40VDC). Subsequently, one can look at numerous small converters that spread out heat over large areas and have not-too-tall components.

Low Voltage vs. High Voltage?

Imagine a scenario where one has 40 small 100W micro-inverter PCB's that spread out heat over 20 square meters (0.5 sq meters per PCB, 2 x 10 meter panel). Each dissipates 2W (98% efficient) and is bonded to aluminum plate to loose heat. If each PCB cost $10, for example, then our cost per watt for 40 of these would be $0.10, which is reasonable (10*40/4000).

Question: Is it less costly to do this with larger voltages (e.g. 400VAC/0.25A per micro-inverter, 40 in parallel, high voltage switches, more offset distance between layers, higher cost for internal electrical insulation) or lower voltages (e.g. 50VAC/2A per micro-inverter, 60V MOSFET IC, lower offset distances between layers, less electrical insulation cost)?

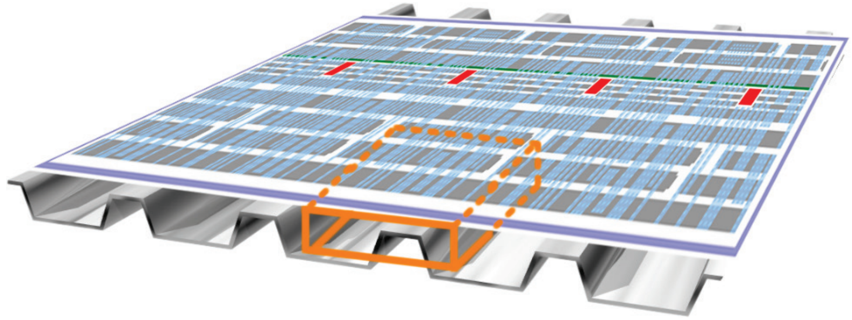
Also, if lower voltage is less costly, would it be helpful to create higher voltages by putting these in series? For example one might place eight 50VAC/2Amps inverters in series to produce 400VAC/2Amps.

AC or DC?

Let's assume we have converters every 300W that connect to 48V/6A PV panels and convert to either 40VDC/7A *or* 30VAC/10A. Also, assume the outputs are assembled in series to produce higher voltages, to 300VDC/8A *or* 120VAC/10A. In the latter case, we have could have grid tie 120VAC ready to go shooting out of panels. In the former case, we would need an additional DC-to-AC conversion in an off-panel box of electronics. Researchers can evaluate both options. For details on the DC option, search this document for "300W DC-to-DC Converters" which shows how to build a DC based.

Space for Embedded Electronics

Each laminated system has a different amount of space for embedded electronics. If system includes 2" thick corrugated steel, for example, then one could place a box of electronics within corrugated layers, as shown to the right in orange color. Other systems might entail 20mm (0.8") thick material with 8mm tall electronic components.



Minimum Bend Radius

Each solar material and layered lamination system has a minimum bend radius. Subsequently, some systems need to be mounted on flat corrugated steel, whereas others can be rolled. Rolls might vary from small (e.g. 0.1m radius) to large (1m radius).

If one takes a 6 inch wide Si wafer, for example, and deflects 0.5 inches (1/12th), then the corresponding circle has a 1 meter radius, as noted here (36in radius = $(6^2 + 0.5^2) / (2 * 0.5)$). Alternatively, a 1.5m radius corresponds to a 0.3in deflection. If one holds a 0.008in thick silicon wafer on one side and deflects by 0.5", then force applied is 0.03LBs.

Many materials that appear rigid will in fact bend slightly. Many traditional photovoltaic materials are kept flat, yet not all. *See Also:* Flexible Monocrystalline, bending test and mechanically flexible silicon.

Electrical Interconnections between Adjacent Panels

Panels in theory can support connections between each other, and this is an exciting area of research for both electrical and mechanical engineers.

What is Standardized and what is Flexible?

We define several things that are standard, yet also provide much flexibility for designers of panels and arrays of panels. Exactly what is controlled by a standard and what is flexible deserves further consideration.

Software Standards

S^3 defines communication protocols for PCB's within a panel (e.g. CANbus two wire network), as well as for panels within an array (e.g. Ethernet fiber network).

Connector Electrical Specifications

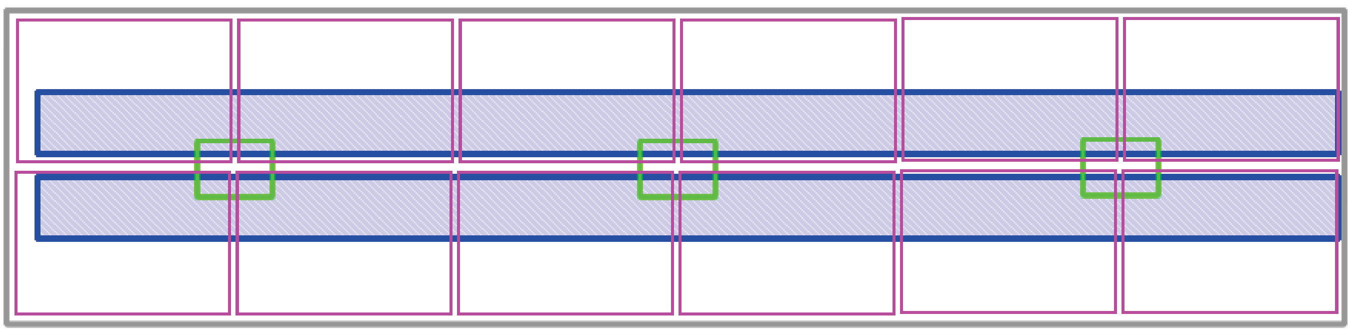
S^3 defines electrical connector specifications that determine the use of each connector pin. If one is concerned about pin failure, they can placed the same signal on two pins (i.e. redundancy) to reduce mean time between failures for each signal.

Power Bus via Metal Plate

The illustration below shows how one might embed PCB's (green) along the center of a 2x10meter panel, where each PCB services four 300W regions of solar material (each region, shown below in violet color, is 1.5m^2). Sheet aluminum in blue color is used to carry current and provides a heat sink for electronics.

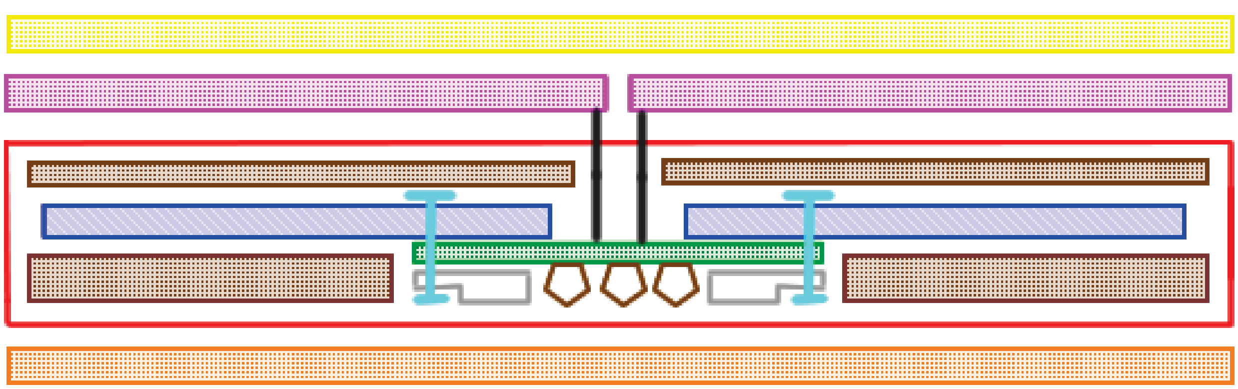
In another example scenario, one could look at having four 1000W converters within a 2x10meter panel with taller components and a heavier heat sink system .

One can do cost models of the various approaches to get a better sense of an optimal system for various component heights.



Aluminum Power Bus Plate Carries Current and Provides Heat Sink

To reduce heat, one must thermally connect hot components to power bus plate (blue). And power bus plate needs to be thermally exposed to top surface. The below illustration shows an example stack-up for building integrated PV material, looking in from the end (e.g. 2 meters across x 10mm high). Glass is yellow, solar PV is purple, PCB is green, power bus plate (and heat sink) is blue (e.g. each plate is 0.5mm x 90cm x 10m and weighs 25LBs), insulation is brown and base support material is orange (thermal insulation, mechanical support).



Aluminum Foil Surrounds Conductors and Electronics in order to Reduce RFI Emissions and Enable Ground Fault Protection

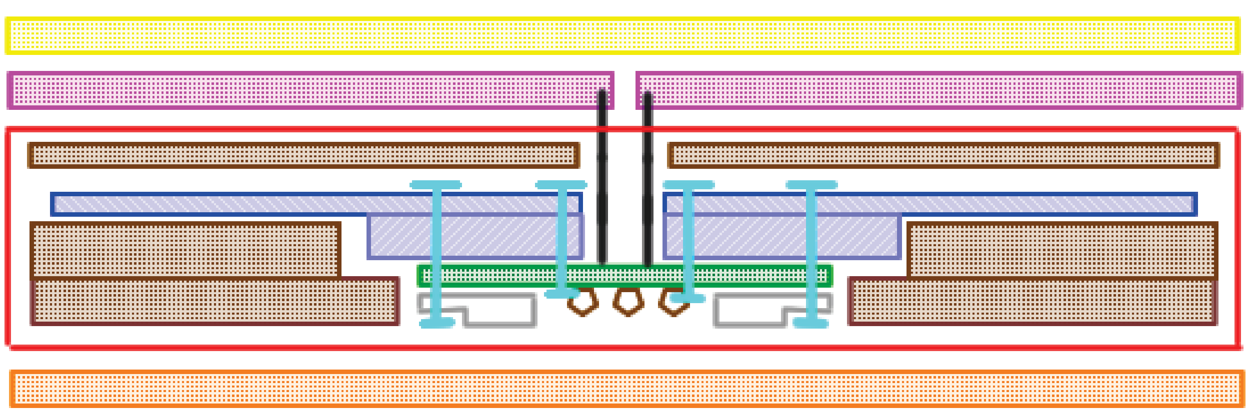
One could potentially envelop conductors and electronics with Aluminum foil (shown above in red); and connect this foil to earth ground. This reduces RFI radiation and also enables ground fault protection (GPF). One measures voltage across this foil and if it is detected, then one concludes that insulation has failed and a conductor is making contact with the GPF shield. Subsequently, one might shut down all circuits and then power up each, one at a time, to see which one is in fault. Faulty circuit is permanently taken out of service.

Transfer Heat from TO-220 Components to Aluminum Plate via Rivets

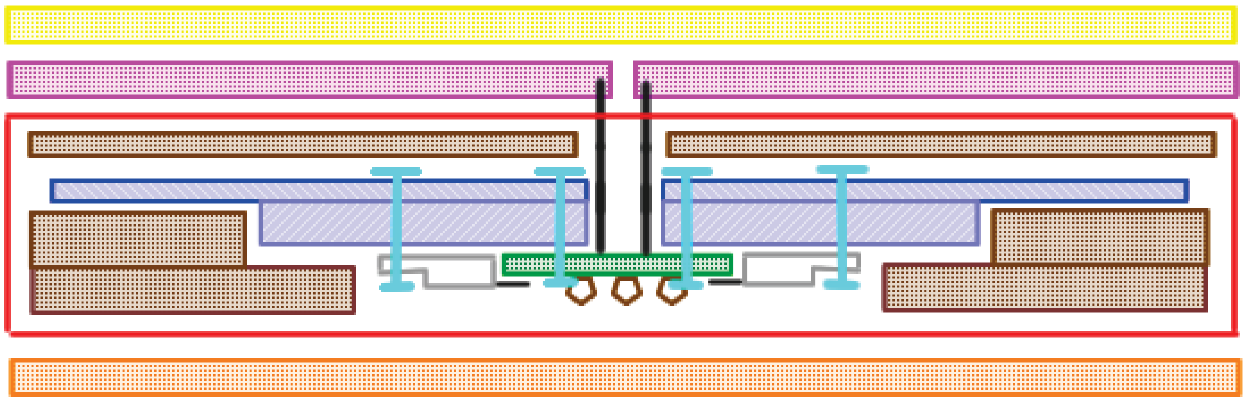
In the above illustration, heat is transferred from TO-220 MOSFET (gray) to aluminum conductor via rivets (turquoise). In this concept, all components are on bottom of PCB and top of PCB is flush against heat sink (common bus plate), to help move heat from PCB to heat sink.

Heavy Heat Sink System

If one works with larger inverters (e.g. 1kW each) then one needs a larger heat sink system for each inverter. If we increase the thickness of the aluminum power bus plate four-fold (i.e. 2mm instead of 0.5mm), then two plates would weigh 214 LBs total raw material cost would be $174. We gain mechanical strength from these plates; therefore, the bottom layer (orange) does not need to be metal, and instead can focus on thermal insulation requirements (to stop heat in the event of solar fault). Alternatively, to reduce weight and cost, one might stack 2mm x 10cm wide plate on top of 0.5mm x 90cm plate, as illustrated below.



Alternatively, one might rivet TO-220 components directly to heat sink metal, via thermal interface pad, as shown below.



In our previous discussion, we looked at embedding DC-to-DC conversion into solar material. We will now look at DC-to-AC conversion using low cost and low height components (e.g. 8 to 15mm). There are disadvantages and advantages to the various sizes (e.g. 100W vs. 800W). Smaller has less height (smaller minimum radius if material is rolled), better fire prevention (smaller amounts of power switched off in event of fault), and spreads out heat more (less temperature). In theory, one could do cost models on the various size options and optimize.

If against plywood, one can have a fire prevention on/off/bypass switch every ~50W and also have larger micro-inverters (e.g. 400W).

Redesign Existing Reference Design

Microchip has a reference design for a 220W grid tie micro-inverter that supports 110VAC current source output.

> Microchip's Grid-Connected Solar Microinverter Reference Design
> https://www.microchip.com/developmenttools/ProductDetails/PartNO/Grid-Connected-Solar-Microinverter

If we drop power 10-fold to 22W, for example, then we can look at resulting size, and cost, and height.

We look at this 2 ways. One is where we drop output voltage 20-fold (6VAC output) and keep input voltage the same. The other is where we keep output voltage the same (110VA) and drop both input and output current 10-fold. To see a partial completed design that shows the reduced 22W version, see file: GWeinreb_Manhattan2_ResearchNotes.xlsx.

				220W Ref Design		Reduction Multiple	6VAC 25W Design		Reduction Multiple	110VAC 25W Design
Power Input		Watts		220		8.8	25		8.8	25
Efficiency		Ratio		90%		1	90%		1	90%
Input	Voltage	VDC		48.0		10	4.8		1	48
	Current	Amps		4.13			4.7			0.47
Output	Voltage	VAC		110		20	5.5		1	110
	Current	Amps		1.8			4.1			0.2

- 6VAC Output Redesign: The 6VAC 25W redesign works with lower voltages, and can therefore accommodate low cost and less tall parts (e.g. ≤ 5mm tall). If we have 10 of these in parallel to create one bank and 4 banks in series, we can build 110VAC (30VAC * 4 = 120VAC), in theory. It looks like this fits into 5mm height with significant cost reductions on important parts. However, one typically cannot place current sources in series. So one would need to either build an interface between the current sources, convert this to voltage source & balance voltage, use transformer to convert low voltage to higher voltage, or something else. This is all a bit complicated and deserves further consideration.

- 110VAC Output Redesign: The 110VAC 25W redesign is similar to the above redesign, yet outputs higher 110VAC voltage. The higher voltage increases parts cost and component height to 12mm. If one works with these higher voltages, it might be cost effective to also work with more power (e.g. 200W instead of 25W).

How does one combine many small, low voltage inverters into one system?

If one combines low voltage current source elements in series (each "element" is a microinverter), they would need to be coordinated in a system to keep current identical, and keep it flowing (normally current sources in series is not done). This would require additional circuitry. If one has multiple strings in parallel, and they are current sources, they combine easily.

If one combines voltage source elements in series, then one can build higher voltages. If you have multiple parallel strings of voltage sources (e.g. sixteen 440VAC voltage sources, one from each 2x10meter panel) and you want to combine them, then that is tricky as well.

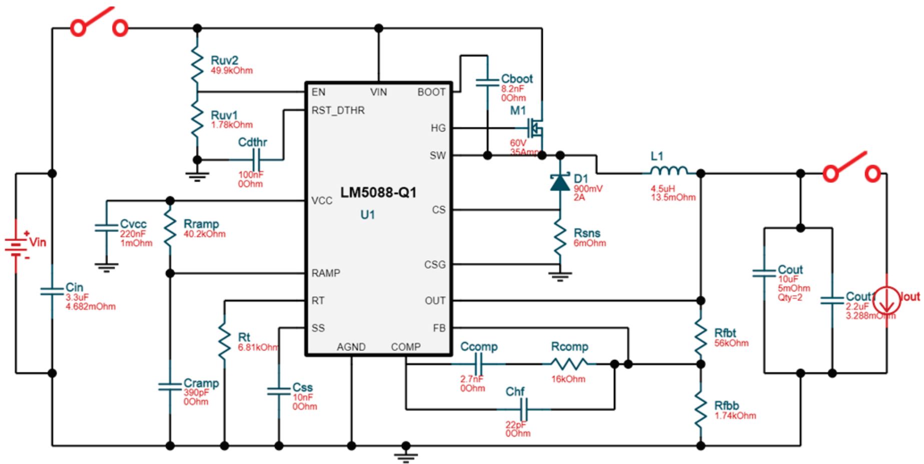
If one has many small inverters (e.g. 25 to 700W) built into a large panel (e.g. 2x10meters), one can add system electronics to coordinate each of these elements into a system. The thinking here is a bit different from having one independent micro-inverter per 3x5ft panel, with little coordination between them.

Possibly Combine Many Small AC Current Sources in Parallel

If each 25W 5mm tall micro-inverter has a 30VAC/0.8A *current* source output (non-isolated, low voltage), for example, and you string all of these together in *parallel* to form 30VAC/128A/4kW, then in theory, you could feed this into a 1-to-4 ratio transformer to convert to 110VAC/32A. An existing power transformer product that is similar to this is:

7K VA, 2:1 ratio, 220-to-110VAC, 60Hz, 150LBs, $500 (quantity 1), Sola HD #HS5F7.5AS. This price works out to $0.12 per Watt, which is high. 150LBs (70Kg) is high too.

Safety Switches Enable Isolation at Input and Output



If multiple current source circuits are in parallel (e.g. 200W * 80 = 16kW), and a current source circuit fails, one would not want the entire system to fail. Also, if a converter input capacitor fails and places a short circuit across its input, one would not want fire. Subsequently, one might place switches at both input and output to isolate in event of fault, as illustrated above in red color. An example switch might be a $0.50 #PSMN012 mosfet, discussed previously. This would provide three different ways of disabling a faulty converter (i.e. input switch, output switch, converter Enable). Two switches might incur a 0.27% power loss (0.13% * 2) and $1.00 parts cost ($0.50 * 2), yet might be worth it due reducing panel-wide MTBF.

What does one do with Higher Currents & Lower Voltages that exit Large PV Panels?

Assume embedded electronics are producing lower DC voltages and higher currents on a common bus plate (e.g. 30VDC on wall, 100VDC on roof). Now, what happens when we go off-panel?

One might think about three different applications: residential (e.g. 5kW to 20kW, 110/220VAC system output, grid tie), commercial roof (e.g. 100kW to 1MW, 440VAC system output, grid tie), and solar farm (e.g. 1MW to 100MW, 1KV to 30KV AC or DC site output).

Let's assume we are working with high currents. Below are 12 example scenarios for power exiting large panels that contain embedded low voltage circuits:

30VDC:	4kW/133A,	8kW/266A,	16kW/532A,	32kW/1064A
60VDC:	4kW/66A,	8kW/133A,	16kW/266A,	32kW/532A
120VDC:	4kW/33A,	8kW/66A,	16kW/133A,	32kW/266A

Let's also assume we have a chassis off-panel that is physically set up to handle a large current bus. And, let's assume we have multiple circuits working in parallel since low cost components tend to not support hundreds of Amps.

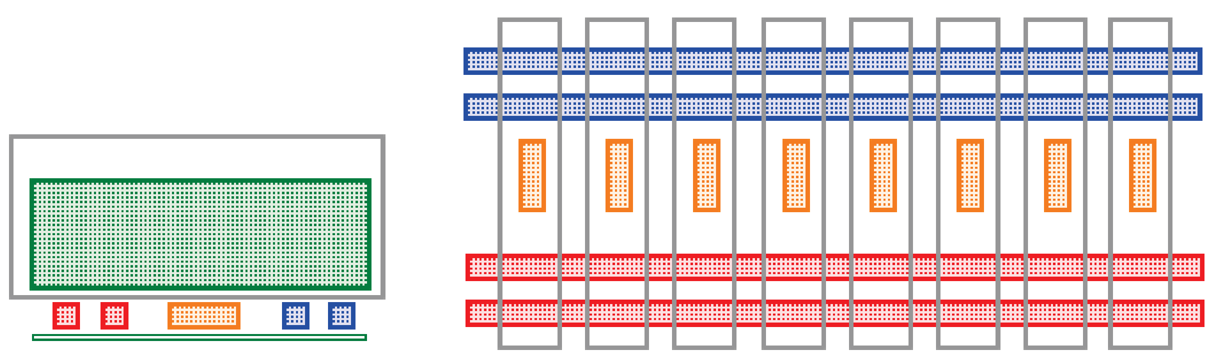
The first thing one might do is increase the DC voltage. If we are ultimately creating 110VAC, we might want 400VDC to feed a DC-to-AC inverter. Or 600VDC for 220VAC, or 1200VDC for 440VAC.

One possible approach is to divide the input power into 8 parallel circuits that each increase voltage and reduce current (e.g. 10-fold reduction) with a DC-to-DC current output converter. For example, if panel array total output is 60VDC/16kW/266A one might have each of the 8 circuits convert 60VDC/2kW/33A to 300VDC/2kW/6A via a fly-back transformer. The outputs would then combine in parallel to produce 300VDC/16kW/48A.

Alternatively, one might have each of the 8 circuits create an isolated voltage source and combine them in series to build a higher DC voltage. For example, if panel array total output is 40VDC/16kW/400A one might have each of the 8 circuits convert 40VDC/2kW/50A to 37VDC/2kW/48A isolated voltage source. The circuits would then combine in series to produce 300DC/16kW/48A.

These two approaches each have their advantages and disadvantages.

How might one implement this physically? Below is one possible approach.



High current enters chassis on aluminum bus bars (e.g. 2cm x 1cm, blue). Eight modules (gray) convert the low voltage / high current to low current / high voltage and place this on the high voltage bus bars (e.g. 0.5cm x 1cm, red). Each module is bolted to 4 bus bars to make good electrical contact, and is replaceable in the event of failure. Also, a connector (orange) interfaces module PCB to motherboard PCB. Perhaps each module is implemented with a ~$2 microprocessor with timers and analog comparators for DC-to-DC conversion, and is networked via CANbus. Each module contains a PCB that is surrounded by an aluminum extrusion. Heat is transferred to extrusion fins in air. Rectangular ports in chassis door enable these fins to poke out of chassis and into air.

After you get your higher DC voltage, then you can convert to AC via traditional methods.

Perhaps each module includes DC-to-AC conversion as well and fully supports power (e.g. 2kW per module)? Subsequently, one can load chassis as needed so that conversion electronics size better match's user requirements, to reduce wasted money on excess electronics capacity.

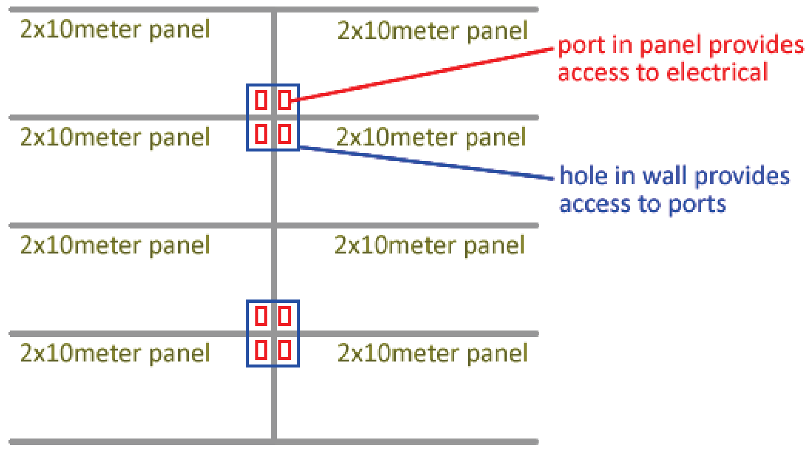
For an example circuit that converts 40VDC to isolated 37VDC/48A/2kW, one can see TI's WebBench design report. For details on the IC featured in this report, please click here. This suggests mosfet #NTP5860 (60V, 220A, 11mΩ, $1.40) for M1/M2/M3/M4. To reduce power loss, one might instead utilize something like two #NVMFS5C604 in parallel for each position (60V, 274A*2=550A, 1.2mΩ/2=0.6mΩ, 1.06*2=$2.12). This would reduce power loss from each of four positions from 15W (71^2*0.003) to 3W each (71^2*0.0006). In positions M5 and M6, one might consider something like two #TK72E12 in parallel for each position (120V, 72A*2=144A, 4mΩ/2=2mΩ, 1.90*2=$3.80). All six Mosfet positions cost something like $16 (3.8*2+2.12*4) for 2kW, or 0.008 per Watt, which is reasonable. The transformer that satisfy the design requirements might be costly (e.g. Lp=1.3mH, Rp=3.4mΩ, Ns1toNp=1.0, Rs1= 15.4mΩ, Ns2toNp=1.0, Rs2=100.0mΩ). If one cannot find a cost-effective transformer, then how else might one implement this circuit? DC-to-DC isolation via flying capacitor? Fly-back transformer that increases voltage 8-fold, decreases current 8-fold, and then combines outputs in parallel (which requires high voltage components)?

In order to get a better sense of lowest cost approach, one could do rough designs for a variety of circuits, build cost models, and compare.

Are heavy transformers feasible in this application?

Recall there are several applications: solar on commercial corrugated steel (Ap3), solar on land (Ap5), solar on metal ribs (Ap4), and solar direct to plywood (Ap1). Heavy components might be acceptable with corrugated steel on land (Ap5), and corrugated steel on commercial roof (Ap3) since these sites utilize heavy equipment such as cranes during installation. However, the land and commercial roof applications might also favor 1000VDC strings that route to 1KV-to-660VAC off-panel inverters, or some other approach that does not involve 60Hz transformers. The solar direct-to-building-surfaces application, on the other hand, might be looking for thin material (e.g. 5 to 12mm height electronics), yet it is not clear if heavy components would fit into that scene.

The illustration to the right shows how panels might be merged at their corners, on a 4 x 20 meter matrix. It is here that further combining could be done. For example, one might have one transformer that supports 16kW from four large panels (e.g. 60Hz 16KV transformer with 4 primary windings and 1 secondary winding that steps up 30VAC to 120VAC).



Summary

In summary, researchers can look at different ways of processing solar energy in several different applications; where each application has their own set of requirements. Researches can develop rough cost models for the various components, to get a better sense as to lowest cost approach given various component heights.

It seems like the lowest cost method of achieving higher voltages is to add isolated DC-to-DC converters in series where each utilizes cheap low voltage components (e.g. eight 300W/40VDC converters create 300VDC), as detailed in our previous Chapter "DC-to-DC Optimizers Embedded...". Also, one can explore alternatives, as we did in this chapter.

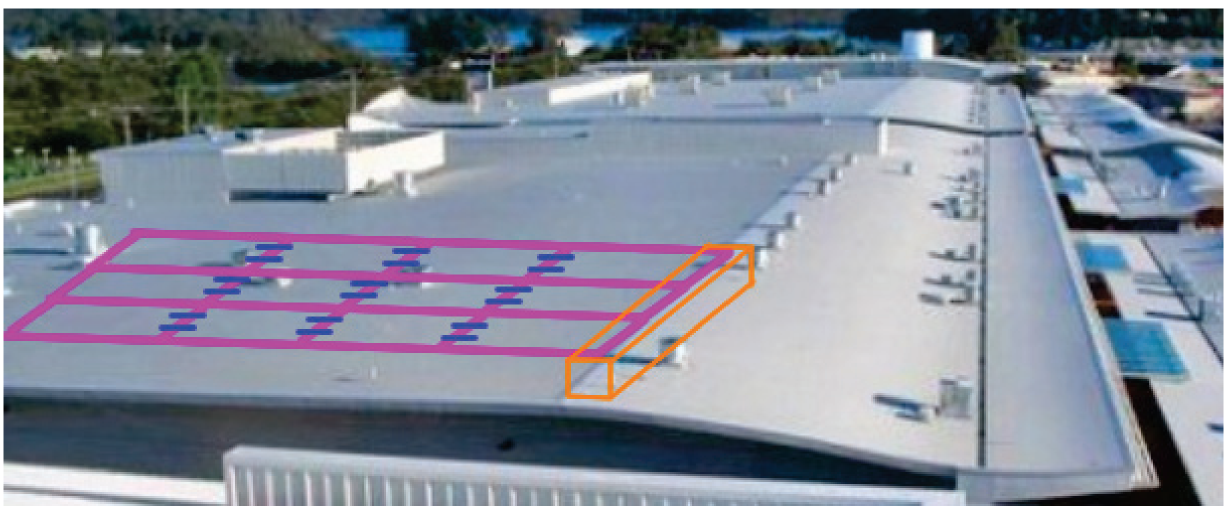
Power Bus Plate in one Panel

If you move 18A on two aluminum rectangular power bus "wires" (current source+-) that are each 10meters long x 30cm wide x 1mm thick, for example, they would dissipate (loose) 0.6W of heat (18A, 0.016V drop), each would weigh 8Kg, and bare aluminum cost for both would be $29. For details see "Voltage drop along rectangular conductor" in file GWeinreb_Manhattan2_ResearchNotes.xlsx.

Power Bus through Multiple Panels in one Row

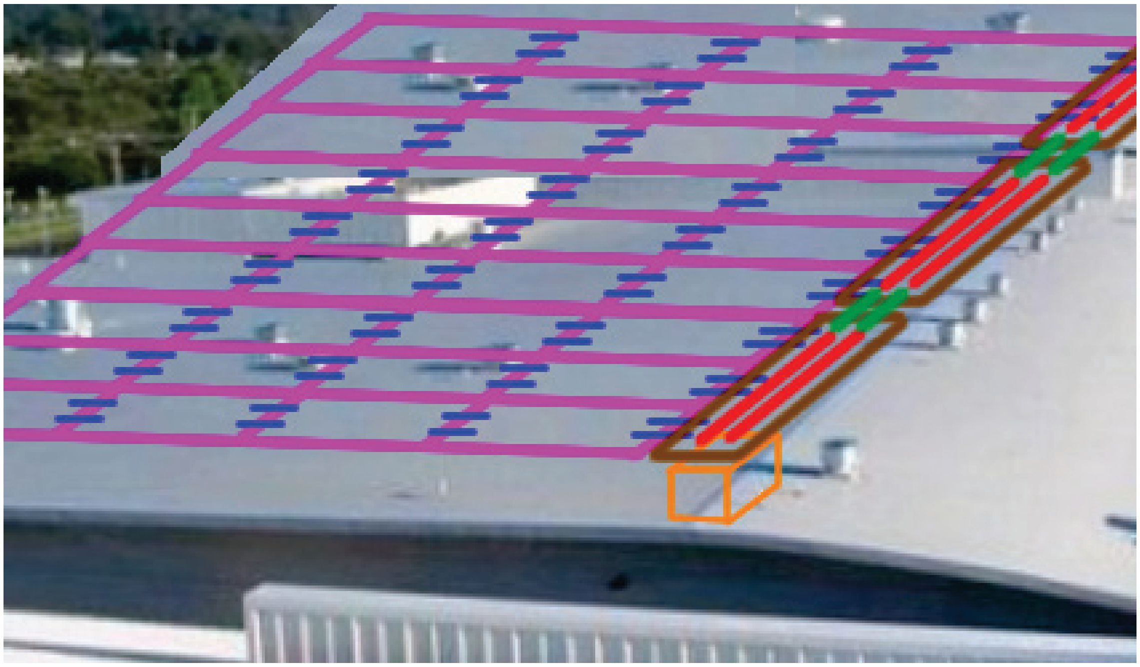
If one has a 3x3 array of large 2x10meter panels, for example, they might run electricity between panels, as illustrated below. This might involve overlapping metal bus plates bound with machine screws (blue).

An equipment bay is shown in orange color under the apex of the roof, inside the attic. It is here that one could place off-panel high DC voltage inverters (e.g. 1kVDC-to-600VAC, 10kW) or combine large current sources (e.g. 4kW/220VAC/18A per 2x10m panel).



Power Bus for Entire Array

If one places large panels (e.g. 2x10m) in a physical array and each contains a 4kW/220VAC/18A/60Hz current source (e.g. made w/ multiple inverters), for example, then one can look at a standardized plug-and-play system for routing current to one position under the roof, as illustrated below. Interaction under the roof in the attic at one position (orange), as opposed to many, typically saves cost. Electronics and conductors embedded in panels enables one to avoid intermediate metal mounting rails and water barrier found in many traditional systems, which further saves cost.



In the above illustration, we combine rows with a master bus system shown in brown color. The master bus contains conductors (red) that are bound together, perhaps with overlapping joints (green).

Let's look at an example array with 5 panels in each row (5 x 10 = 50meters, 18A * 5 = 90Amps), 20 columns (20 x 2 = 40meters), and 2x10m panels that each produce a 4kW/220VAC/18A current source. Total current on the master bus works out to 1800A at 220VAC (5 x 20 = 100 panels, 4kW * 100 = 400kW, 90A * 20 = 1800A). If master bus conductor passing 1800A is 40m long x 0.9m x 1cm, for example, then it would dissipate 800W (lost heat), weigh 4200LBs, and cost $3500 for raw material.

We are not recommending this exact system; instead, we are just looking at one example approach and running the numbers.

Electronics Integration

Researchers can *compare* embedding switching electronics within large panels *vs.* placing resources off-panel. Equipment bays inside a building to house electronics must be designed, built, inspected, and maintained. And at what cost? If cost is high, embedding electronics into plug-and-play standardized solar material becomes more interesting. Engineering and installation labor costs are high; therefore one might find it cost effective to spend more money on embedded electronics, and less on engineering/installation labor within a building.

Installation

If large solar panels are heavy (e.g. 2x10meters, 200 to 1000LBs), then one would need a crane or truck with articulating arm to help with installation.

Specific Requirements for Each Application

Let's review the different applications, each of which have their own set of requirements.

- Corrugated Steel Panels on Commercial Roof (Ap3)

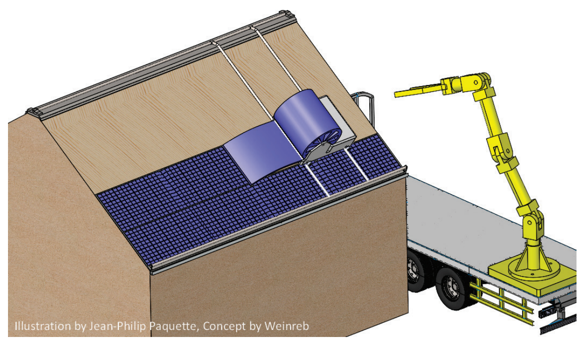
  This is similar to solar on land, in that one *might* favor high voltage strings that feed big off-panel inverters (e.g. 1kVDC-to-660VAC/10kW). However, fire control might be more important since fire on a building is bad (i.e. more internal bypass switches). Access to underneath surface is not as easy as on land; therefore, one might favor routing of power within panels to avoid power cables in difficult to access places under roof. If roof has insulation pressed against bottom surface (e.g. in attic, pressed against roof), then one needs to vent electronics heat to top solar surface. One might also look at ~300W DC-to-DC converters (e.g. low cost, 8mm height parts, MPPT, supports bypass, shuts down in event of fault, spaced every 1.5m^2). These might be combined in series to produce a high DC voltage (e.g. 1000VDC) that feeds an off-panel inverter (e.g. 2nd stage of typical string inverter, 1000VDC-to-440VAC).

- Solar on Metal Ribbed Roof (Ap4)

  In theory, one can roll down solar material on top of a metal ribbed roof via a variety of techniques (or drop flat pieces in via crane). This application might require: fire control, routing of electricity to one location via internal conductors, and thin solar material (e.g. 10 to 20mm). It is not clear if it is better to embed many low-height converters into the material, or position more electronics off-panel. Researchers can develop cost models for various approaches to get a better sense of how to proceed.

- **Solar mounted Direct to Plywood Roof or Wall (Ap1)**

  This is similar to Metal Ribbed Roof, described above, yet fire control is more important due to combustible wood which burns at 300°C.

  Plywood provides rigidity which allows us to utilize light-weight solar material, which would hopefully translate to reduced cost (due to less material). Obviously, this requires a mechanical system for attaching solar to plywood, and an installation system that facilitates assembly in the field.

  Our solar material becomes the water barrier since we are attaching directly to plywood and we cannot have anything above us. This might seem scary at first, yet note that corrugated steel panels in commercial roofs include overlapping joints and these have a long history of managing rain water.

  A variation of this system is to skip plywood and instead drop in rigid corrugated steel or aluminum panels and attach directly to wood or metal framing.

- **Elevated Solar on Land (Ap5)**

We have plenty of space under solar material, therefore electronic height is less important. Lowest cost might be something like 10kW strings to off-panel 1kVDC-to-660VAC inverters (or inverters integrated into corrugated steel panels). Researchers can compare this with smaller converters (e.g. 300W) embedded in solar material. One can vent heat out the top or bottom surface. Panels are required to provide rigidity and strength, and maintain shape during high winds. If working with large DC voltage strings (e.g. 1kVDC/10A), one can embed bypass switches every X Watts (e.g. 500W), to bypass under-performing or faulty cells.

- Land Integrated PV (Ap2)

  This is similar to elevated solar on land, yet material strength is less of issue due to mechanical support provided by land. Managing rain water, soil erosion, and up-ward pulling pressure from wind all become serious issues when placing solar directly against soil.

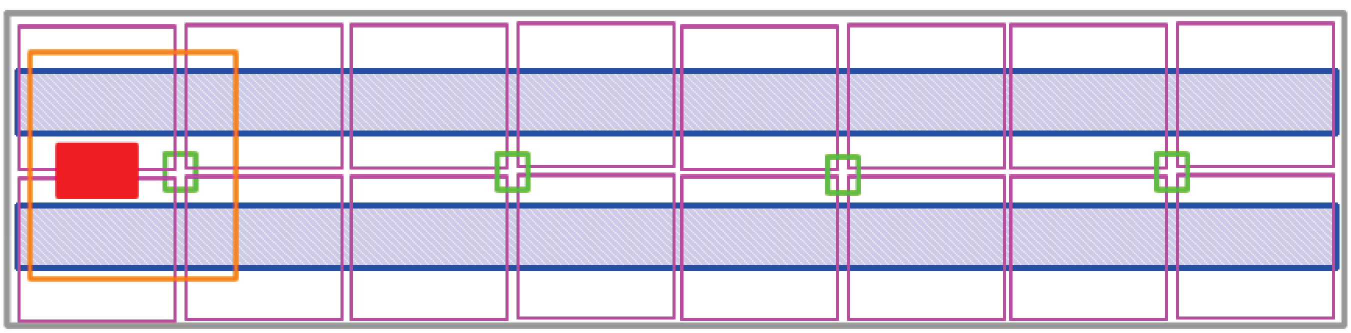
In previous chapters we looked at low height (e.g. 12mm) embedded electronics. We now look at what one might do with more height and higher voltages.

One Large Inverter per Panel

In theory, we could integrate *one* large inverter into each large panel. For example, one could feed a 1kVDC/4A voltage string from a 2x10meter panel into an inverter that produces a 660VAC/5A current source. If inverter is 1.5" (38mm) thick, it could be mounted into a 2" (50mm) thick 2x10 meter panel, for example.

System Design

The below illustration shows what this might look like. Small PCB's (green) contain bypass switches that remove cells (purple, 250W) if underperforming or in fault (e.g. fire). The inverter (red) is connected to a 2mm x 1 square meter flat aluminum heat sink on underneath surface (orange). This 2" thick panel could stack on the back of a flatbed truck or stack inside a shipping container; and could easily be assembled, plug and play.

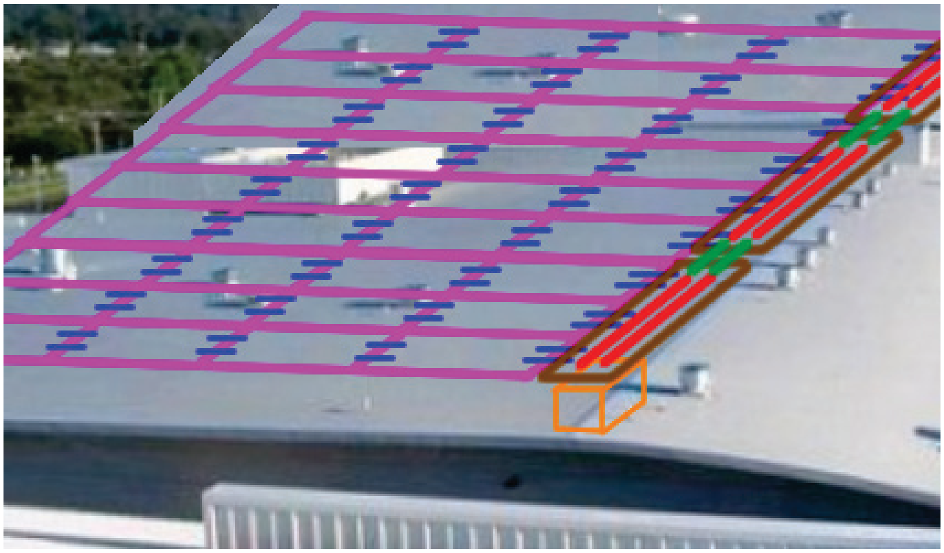


Heat Sink

If 4kW string inverter is 95% efficient and sheds 200W, and heat sink allocates 0.5 Watt for each square inch, then one might utilize a 20x20inch flat plate heat sink (0.25 m^2). If one is generous and moves to 1 square meter (4 times more) and 2mm thick (i.e. 5Kg, $10 bare AL cost), then inverter would stay cooler and potentially last longer. One could expose this plate to the panel underneath surface if on land (solar farm) or the underneath surface of a corrugated steel panel if there is no insulation at that location. If one cannot shed heat to underneath surface, then one must push heat to top panel surface, perhaps via a very large internal power bus plate pressed against top surface. Mechanical modeling software can help design a heat sink system, and take into consideration thermal conductivity of materials above power bus plate.

How to Coat the World With Solar?

In theory, one could develop a system for combining these, plug-and-play, with minimal engineering time and labor at building site, to reduce cost.



This could be done with a standardized system coupled with free and open reference designs for all system components. Standards would include electrical connections, mechanical systems, communications protocols, etc.

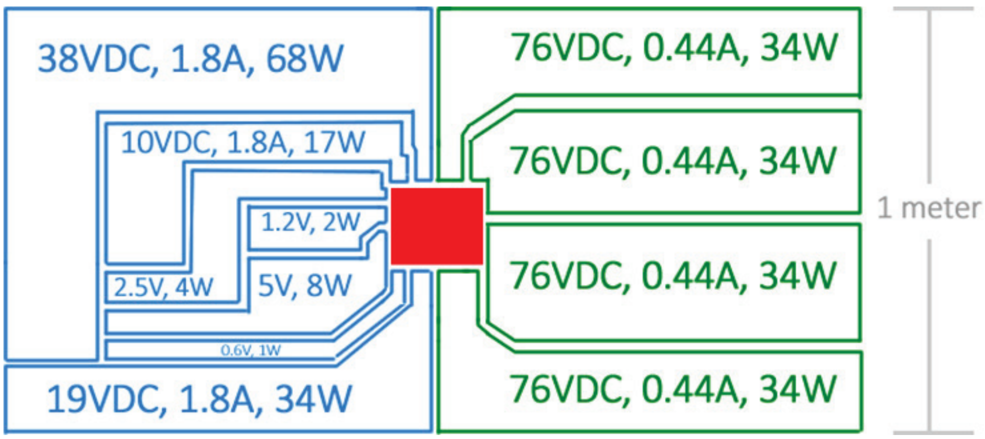
How would the world respond? If these things give money to their owner (i.e. produce electricity) and are cheap, they might see viral adoption.

A standardized mechanical system is needed for each application, including solar on land (solar farm), direct to plywood, direct to metal ribbed roof, and corrugated steel commercial roof.

A standardized communication protocol that governs how system components talk could be flexible enough to support all applications.

If we have access to each cell, and cells produce different voltages, can we use switches to create waveforms and reduce filtering requirements? Perhaps additional filtering is handled off the panel?

In the below 1x2 meter illustration, cells produce different voltages (e.g. 76V, 38V, 19V, 10V, 5V, 2.5V, 1.2V, 0.6V) that route to an internal PCB (red in illustration).



Binary Math

If one has 4 batteries (8V, 4V, 2V, 1V) that can be combined in series via switches, then one can produce a voltage between 0 and 15V via binary math. Also, this means cells are switched out of the string. These can be combined into another wave which we call the “residual wave”. The residual is a funny shape and needs further processing to be useful.

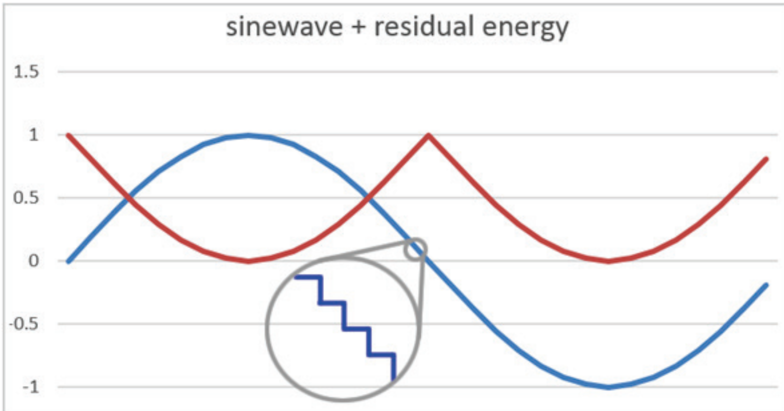
If you have 8 bits (256V, 128V, 64V ... 4V, 2V, 1V), for example, and you build a sine with these, you can get a tiny square wave on top of a pure sine. The square is 1/256th the amplitude of the pure sine, and needs filtering. Yet filtering is somewhat easy if its amplitude is 1/256th size.

Switches on PCB can produce AC and DC voltages at different voltage levels and frequencies, as required by the various components (e.g. ideal power into compressor motor might be 35Hz at 82VAC). The PCB does much of the DC to AC conversion while relying on relatively small external or internal filtering components for cleanup.

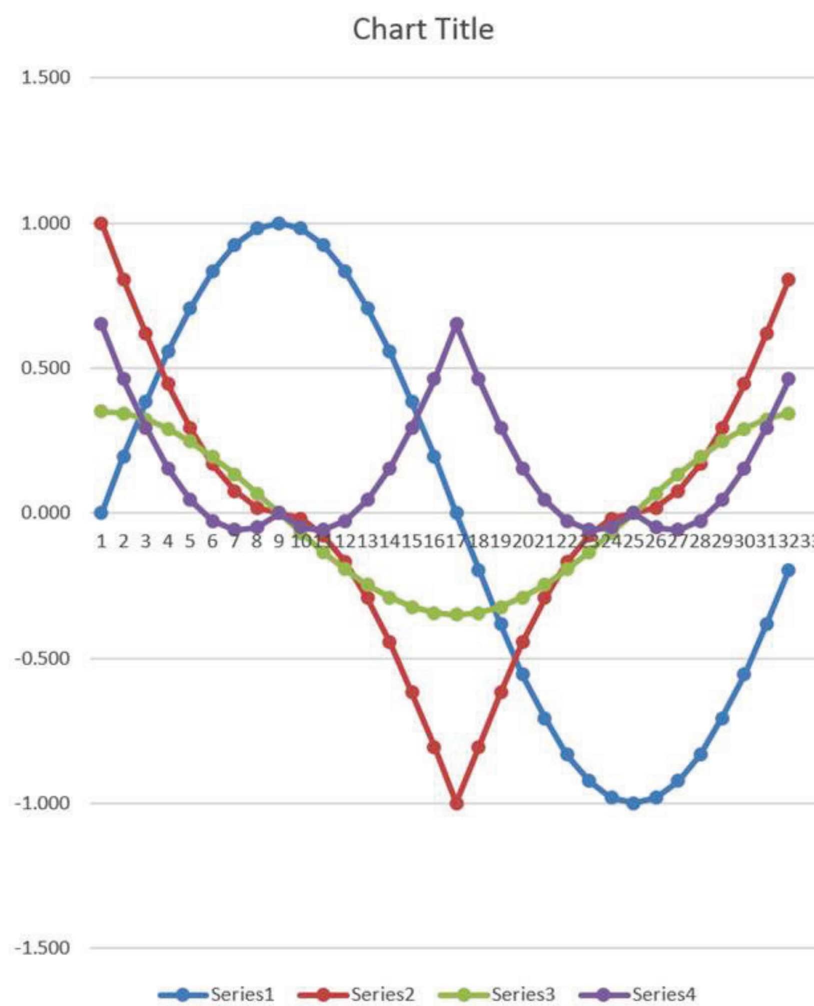
For more details, refer to Manhattan 2 Blueprint Document, Chapter 3, Section "Typical 110VAC 1x2meter Bank".

The Residual Wave

If switches create a sine, then solar cells that are not being used can be combined in series to produce the "residual wave" (37% of total amplitude). Below is what that looks like. Blue is sine and red is residual. If you add these two, you will get a flat line (e.g. DC voltage) at value 1.



Now, what can we do with the Residual? If we flip the polarity of the residual energy 50% of the time, we get the *below* Red "Series2" wave (37% of total amplitude). If we switch out 60% of this (22% of total amplitude) we can create another sinewave (Green "Series3" wave) that is 90 degrees out of phase with respect to the primary sine (63% of total amplitude).



One could take the left over (Purple "Series4" wave, 18% of total amplitude) and build a 3rd wave. Perhaps one gets 3 waves out of the system? Perhaps a small inverter takes some of this residual and builds something? Perhaps Capacitor and/or Inductor stores energy and moves it from residual to pure sine?

One could design a waveform construction system, calculates cost, and see how it compares w/ traditional inverters.

If wave construction cost more money, yet has less height (e.g. 3 to 5mm), then perhaps the higher cost is ok due to applications that want low height and spread out heat (e.g. solar direct to building surfaces).

Or, perhaps higher cost is justified since this system can produce programmable AC or DC voltages (e.g. 82VAC/32Hz, or 40VDC). Compressor motor in HVAC might requested a preferred voltage and frequency to power a variable speed motor. If $2 network connected processors are connected to the network, and their communication protocols are standardized, this becomes possible.

System Design

If one is working with higher voltages and smaller currents, then switches might be lower cost. For example a 500VAC/8A (4kW) system with 8 switching elements would consume 10-fold fewer switches than ten 50VAC/8A (400W) systems.

If one takes a 2x10meter panel with integrated electronics (4kW) and divides it into 4 sectors, 1kW each, and does 8bit switching at each sector, then one would have a total of 32 (8*4) switching elements on the 4kW panel. If each switching element cost $5, then total switching cost would be $160 (32*$5), which works out to $0.04 per Watt, which is reasonable.

If one has 4 voltage sources (e.g. 500VAC/2A/1kW) per panel then one would need more processing to combine them, and combine multiple panels. Perhaps a transformer would be helpful?

Spreadsheet "Manhattan2_PowerWaveConstruction.xlsx" is a helpful tool for evaluating the residual wave.

http://www.ma2.life/doc/plan/Manhattan2_PowerWaveConstruction.xlsx

Switching solar elements of differing voltages might seem strange and complex, and it is. However, many inverters involves much cost and heat. Therefore, alternatives such as waveform construction via switching should be considered.

Questions

- If the design engineer has access to each cell and can specify each cell voltage (e.g. 76V, 38V, etc.), then what can he/she do with this potential opportunity?
- Is cell switching less costly than traditional methods?
- How could one process the residual wave to make it useful?

Chapter 15) Microinverter Reference Designs (e.g. 48VDC-to-110VAC, MPPT, 600W)

Below are several micro-inverter reference designs that include schematics and detailed documentation.

TI Presentation on their all their Power Converter Reference Designs (good)

- PowerPoint: http://www.ti.com/cn/lit/ml/sszp159/sszp159.pdf

Single-Phase Inverter Reference Design with Voltage Source and Grid Connected Modes

- Specification: 380VDC/2A input, 110VAC/5A output, 600Watts, $800 to buy ref design
- Webpage: http://www.ti.com/tool/TIDM-HV-1PH-DCAC
- Manual: http://www.ti.com/lit/ug/tiduay6d/tiduay6d.pdf

Grid-tied Solar Micro Inverter with MPPT, AC Output

- Specification: 25 to 45VDC input, dc-to-dc followed by dc-to-ac, mppt, 110VAC/140W or 220VAC/280W out
- Webpage: http://www.ti.com/tool/TIDM-SOLARUINV
- 600W Version: http://www.ti.com/tool/TIDM-SOLAR-ONEPHINV
- Manual: https://www.ti.com/lit/ug/tidu405b/tidu405b.pdf (good)
- Schematic: http://www.ti.com/lit/df/tidr767a/tidr767a.pdf
- BOM: http://www.ti.com/lit/df/tidr770a/tidr770a.pdf

Grid-tied Solar Micro Inverter with MPPT, DC Output (not AC)

- Specification: 200 to 300VDC input, 400VDC output, dc-to-dc, mppt, 500W,
- Webpage: http://www.ti.com/tool/TIDM-SOLAR-DCDC

Microchip's Grid-Connected Solar Microinverter Reference Design

- Specification: 25 to 45VDC input, dc-to-dc, dc-to-ac, mppt, 215W, 110/220VAC
- Webpage: https://www.microchip.com/developmenttools/ProductDetails/PartNO/Grid-Connected-Solar-Microinverter
- Schematic: https://www.microchip.com/stellent/groups/SiteComm_sg/documents/DeviceDoc/en550277.pdf
- AN #1444: http://ww1.microchip.com/downloads/en/DeviceDoc/01444b.pdf
- Webinar (good): https://www.microchip.com/stellent/groups/SiteComm_sg/documents/DeviceDoc/en550277.pdf

Microchip Grid-Connected Solar Microinverter Reference Design Using a dsPIC Digital Signal Controller, Application Note #1338

http://ww1.microchip.com/downloads/en/appnotes/01338d.pdf

ST Microsystems 250W Microinverter Reference Design, AN4070

https://www.st.com/content/ccc/resource/technical/document/application_note/fa/f1/fe/3d/81/1e/47/45/DM00050692.pdf/files/DM00050692.pdf/jcr:content/translations/en.DM00050692.pdf

TI Solar Conversion Resources

- Application Notes: http://www.ti.com/solution/solar-micro-inverter-diagram
- PowerStage Designer Software: http://www.ti.com/tool/POWERSTAGE-DESIGNER
- 31 Reference Designs (search "solar"): http://www.ti.com/power-management/reference-designs.html#search?famid=64

Low-Voltage and Low-Cost Buck Converters with DC Current Source Outputs

- 100W, #SSC8802: https://www.aliexpress.com/item/32688560973.html
  http://www.southchip.com/Private/Files/20190623220610716%E2%88%AESC8802_datasheet_v0.3.3_en.pdf
- 80W, #CN3722: https://www.aliexpress.com/item/32715786472.html
  http://www.consonance-elec.com/pdf/datasheet/DSE-CN3722.pdf
- 80W, #BQ24650: https://www.aliexpress.com/i/32869090846.html
  http://www.ti.com/lit/ds/symlink/bq24650.pdf

Chapter 16) String Inverter Reference Designs (≥ 4kW, 200…1KVDC in, 220…660VAC out)

10kW 3-Phase 3-Level Grid Tie Inverter Ref Design for String Inverter, Texas Instruments

- Specification: 800 to 1000VDC input, 400VAC output, 10K Watts
  TIDA-01606_Power Card REV E4 Bill of Materials
- Webpage: http://www.ti.com/tool/TIDA-01606
- Manual: http://www.ti.com/lit/ug/tidue53a/tidue53a.pdf

DC to AC String Inverter Commercial Products

- SMA America : https://www.sma-america.com/products/solarinverters/sunny-tripower-12000tl-us-15000tl-us-20000tl-us-24000tl-us-30000tl-us.html
- Best Solar Inverters 2019: https://www.cleanenergyreviews.info/blog/best-grid-connect-solar-inverters-sma-fronius-solaredge-abb
- Fronius: https://www.fronius.com/en-au/australia/photovoltaics/products/commercial/solutions/system-solutions/fronius-power-package/fronius-power-package
  https://www.thepowerstore.com/pub/media/downloads/8694_Technical%20Datasheet.pdf
- Amazon.com Inverters: https://www.amazon.com/Solar-Wind-Power-Inverters/b/ref=dp_bc_aui_C_4?ie=UTF8&node=13638742011
- Amazon > $2.5K Inverters: https://www.amazon.com/s?i=lawngarden&bbn=13638742011&rh=n%3A2972638011%2Cn%3A3238155011%2Cn%3A552808%2Cn%3A3236381%2Cn%3A13638742011%2Cp_36%3A250000-&page=2&qid=1575566088&rnid=2661611011&ref=sr_nr_p_36_1

Solar Inverter Gateway Featuring AM335x, Reference Design, Texas Instruments

- Specification: Solar Inverter Gateway Development Platform Reference Design
- Webpage: http://www.ti.com/tool/TIDEP0044
- Manual: http://www.ti.com/lit/ug/tidua96/tidua96.pdf

Multiple DC-to-DC *and* DC-to-AC Converters, 1kW to 3kW, Transphorm Inc.

https://www.digikey.com/en/product-highlight/s/silicon-laboratories/isolated-gate-driver-plus-high-voltage-gan-fet-reference-designs

Multiple DC-to-DC *and* DC-to-AC Converters, 200W to 3kW, Digikey

https://www.digikey.com/products/en/development-boards-kits-programmers/evaluation-boards-dc-dc-ac-dc-off-line-smps/792?FV=1989%7C0%2C-8%7C792%2Cmu200W%7C2186%7C0&quantity=0&ColumnSort=2186&page=1&pageSize=500

Chapter 17) Combining Multiple Sources of Power

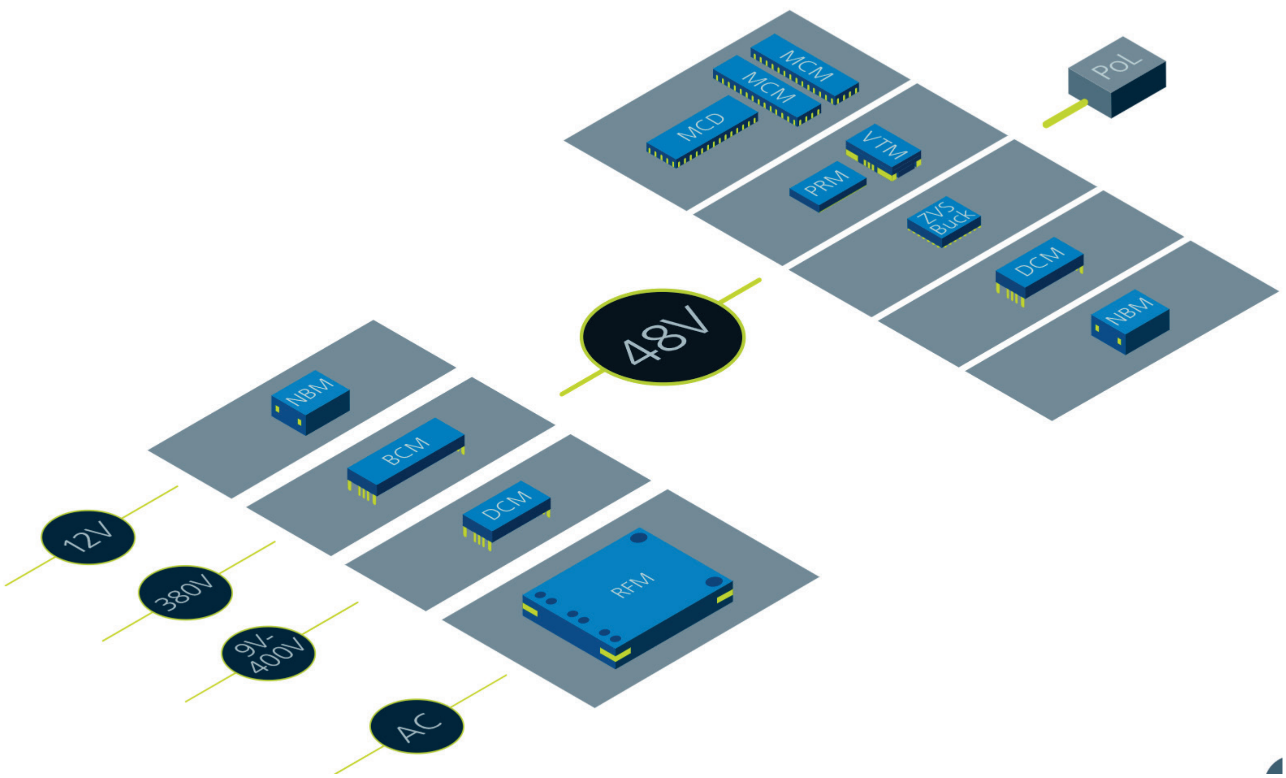
- An Overview of Distributed Energy Resource (DER) Interconnection: Current Practices and Emerging Solutions
  https://www.nrel.gov/docs/fy19osti/72102.pdf
- Distributed Fault Management for Enhanced Protection and Resiliency of Active Distribution System with Nested Micro-grids.
  https://repository.lib.ncsu.edu/bitstream/handle/1840.20/35534/etd.pdf?sequence=1&isAllowed=y
- IEEE 1547 Series of Interconnection Standards
  http://grouper.ieee.org/groups/scc21/1547_series/1547_series_index.html

Chapter 18) Existing Low-Height Conversion Products

Below are existing low height power conversion products (e.g. AC-to-DC, DC-to-DC).

Vicor Power Inc.: 3mm to 8mm tall Conversion Power Supply Modules (costly, low height)

- Webpage: http://www.vicorpower.com/
- Product Family: http://www.vicorpower.com/files/live//sites/vicor/files/documents/family_overviews/fo-BCM-VICOR.pdf



Suggested Research: Develop Standardized Plug-and-Play Solar PV Panels with Embedded Electronics & Conductors for Land, Commercial Roofs & Direct-to-Building Surfaces *(Mechanical or Electrical Engineering)*

Develop next generation standardized PV panels with embedded electronics and embedded conductors. For example, one might design a standardized 2x10 meter panel that stacks on the back of a flatbed truck and is installed via crane. Mechanical engineers design mechanical systems for large solar panels on land (solar farm), commercial roof (e.g. 30x100 meter roof on metal framing), or direct-to-plywood roof or wall (e.g. for residential). Assume automated machinery is available for installation. System must support replacement and/or repair in the event of fault. Using 3D mechanical modeling software; show design and simulation for ~50 years of UV, wind, rain, hail strike, erosion and thermal cycling. Electrical engineers design circuits for embedded electronics and off-panel modules that further process electricity. Researchers may propose mechanical standards, electrical connector standards and communication standards. Researchers may also propose Building Codes and National Electrical Code for Building Integrated PV.

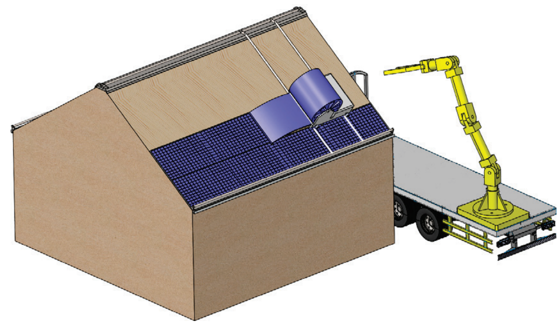
Suggested Research: Develop Mechanical System for Large Solar Panels on Land (*Mechanical Engineering)*

Develop a standardized mechanical system that supports PV panels with embedded electronics and embedded conductors that connect together on land within a solar farm. Mechanical engineers explore flat (e.g. 2x10m panels) and/or rolled designs (e.g. spool of 2x50meter 1cm thick material that rests on metal framing).

Suggested Research: Develop Mechanical System for Large Solar Panels on Commercial Roof (*Mechanical Engineering)*

Design a mechanical system for large PV panels with embedded electronics and embedded conductors that mount on commercial roof. Consider systems where rigid PV panels implement roof structure and water barrier (e.g. 2x10meter corrugated steel panel with built in solar) as well as non-water-barrier systems that are placed on top of a traditional roof. Mechanical engineers can look at flat panel designs or rolled material.

Suggested Research: Develop Mechanical System for placing Solar PV Direct-to-Building Surfaces (BiPV) *(Mechanical Engineering)*



Design mechanical system for placing solar material with embedded electronics and embedded conductors directly onto building surfaces, including both wall and roof. Assume:

- Material provides water barrier.
- Material is supported by installation machinery (e.g. truck with articulating arm accurately routes grooves & drills holes in plywood and handles large spools of rolled material).
- Material is prepared in factory with features using architectural drawings (e.g. cut holes in material at specific locations to support vents).
- Material supports repair and/or replacement.

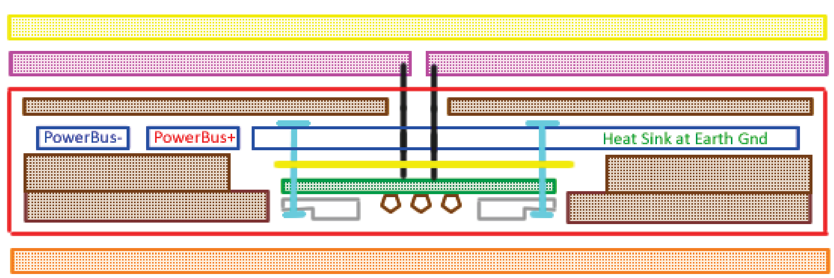
Suggested Research: Develop Embedded Electronics for Large Standardized Plug-and-Play Solar PV Panels *(Electrical Engineering)*

Develop electronics for large standardized plug-and-play solar panels. Analyze the various electrical options, calculate costs, design circuits, and build prototypes. Assume:

- Large solar panels contain two internal bus conductors (e.g. each 0.5mm x 80cm x 10meters aluminum) for routing current, providing mechanical strength, and supporting a heat sink for electronics.
- An embedded electronic converter circuit manages each ~1 square meter of solar for purposes of MPPT (maximum power point tracking), fire prevention (turn off in event of fault), and degradation management (shading one area does not affect entire array). For example, a researcher might design a 45VDC-to-40VDC DC-to-DC converter (e.g. 300W, $25 parts cost, $0.08/Watt, 8mm tall components) that is implemented with a ~$2 microprocessor and networked via CANbus. Note that low voltage non-isolated DC buck converter circuits are typically lower cost and lower height than higher voltage isolated AC circuits (for an example, see this TI design report). If one combines 8 of these in series to produce a 300VDC substring, and then combines 8 substrings in parallel, they could create 300VDC/64A/19kW inside a 1cm thick panel assembly via low cost buck converters, which later drive an off-

panel 300VDC-to-110VAC grid-tie inverter, for example (e.g. 2nd stage of typical string inverter). Combining ~300W circuits is tricky -- researchers need to work out details. Researchers evaluate different voltage/current schemes and look for lowest system cost focusing on three applications: residential (e.g. 5kW to 20kW, 110 or 220VAC system grid tie output), commercial roof (e.g. 100kW to 1MW, 440VAC system grid tie output), and solar farm (e.g. 1MW to 100MW, 1KV to 30KV AC or DC site output).

- System is resistant to faults from internal ~300W converter. For example one might have two MOSFETs that open in the event of fault. One MOSFET might sit between solar PV and converter PCB, and another between converter PCB and common current bus.
- Converter PCB monitors internal nodes via A/D (e.g. input current/voltage input, output current/voltage, capacitance of input capacitor, capacitance of output capacitor, inductance of main inductor, etc.).
- Failure of any Converter PCB component (e.g. to short or to open), or a short circuit between any two nodes, does not create enough heat to cause fire or melt material.
- Converter PCB shuts down system in event of high temperature or current detected on earth ground shield (e.g. due to insulation failure between conductor and enclosure).
- Panels clip together, end-to-end in a standardized way (e.g. four 2x10m panels form 2x40m assembly).
- Assemblies terminate at a spine on land, or cavity inside building. It is here that electricity on bus conductors (e.g. 300VDC, 64A, 19kW) is converted to something more useful (e.g. 110...220VAC for buildings and 660...1440VAC for solar farm) via a string inverter module designed by researchers.
- The illustration to the right shows an example stack-up for building integrated PV material, looking in from the end and not drawn to scale (e.g. 2 meters across x 12mm high). Glass is yellow, solar PV is purple, PCB is green, power bus plate and heat sink is blue, TO-220 mosfet is gray, insulation is brown and base support material is orange (thermal insulation, mechanical support). Aluminum foil (red) is connected to earth ground to reduce RFI radiation and enable ground fault protection (turn off panel in the event voltage is detected at foil due to insulation failure).



- Electrical engineers explore the various options for moving electricity on land and on building surfaces, with rough designs and cost models. Researchers assume they are working with large panels that contain embedded electronics and embedded conductors. For more details, see previous Chapter "DC-to-DC Optimizers Embedded into Solar Material".

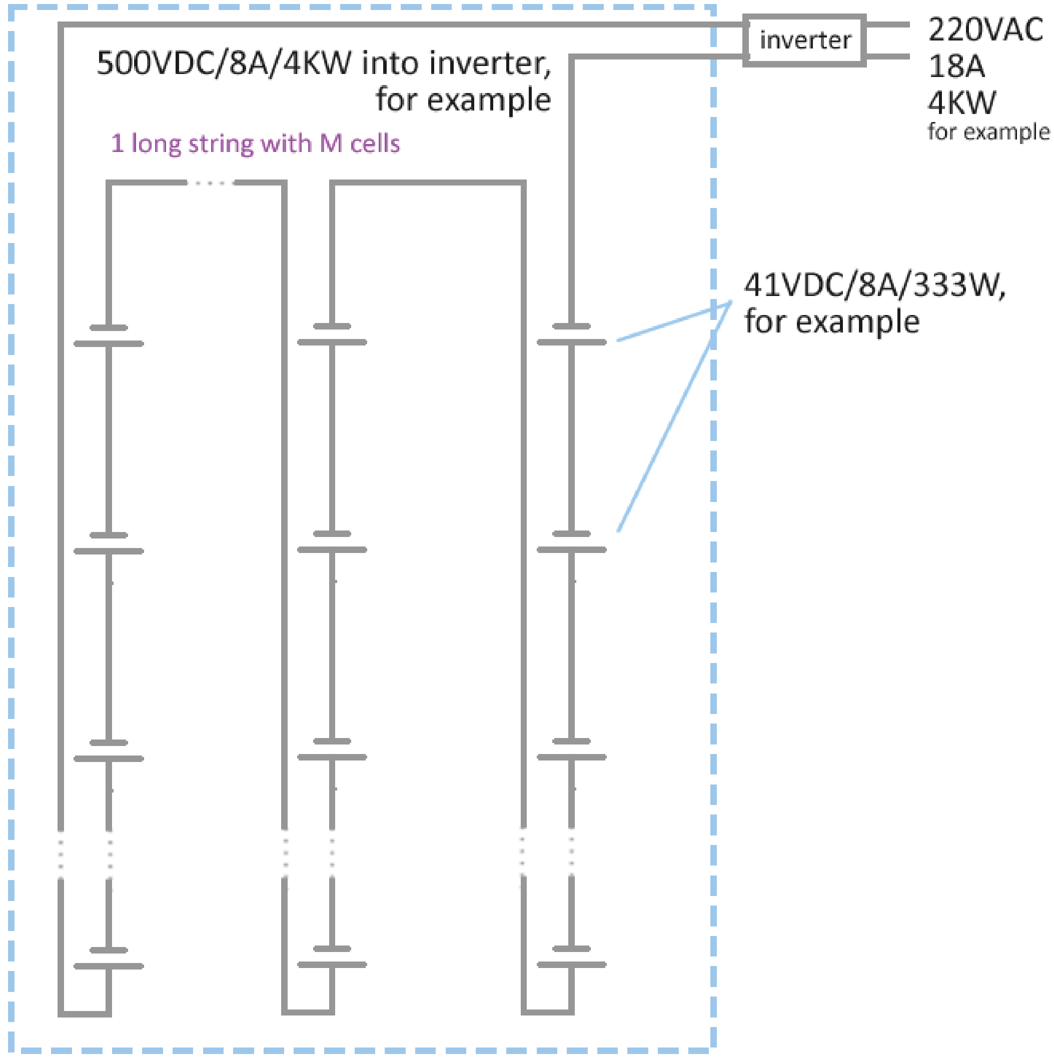
Chapter 20) Multiple Electrical Power Configurations

S^3 supports multiple internal electrical configurations, several of which are described in the following pages. We refer to these as "Electrical Configurations" and give them a designation code (e.g. Ec1 is one long string). Illustrations show example cases and numbers that appear in pictures are for illustration purposes only. The S^3 electrical power configuration standard supports any set of values (e.g. any AC or DC voltage, any panel size).

These help with our electrical modeling and software, since we can refer to these configurations w/ the various parameters that characterize each.

Ec1: ONE LONG STRING, NO ELECTRONICS IN PANEL

This configuration involves one long string with no electronics within the panel; as illustrated below.



Standardized Super Solar Panel, e.g. 2 x 10meters,
includes embedded conductors and electronics

Advantages

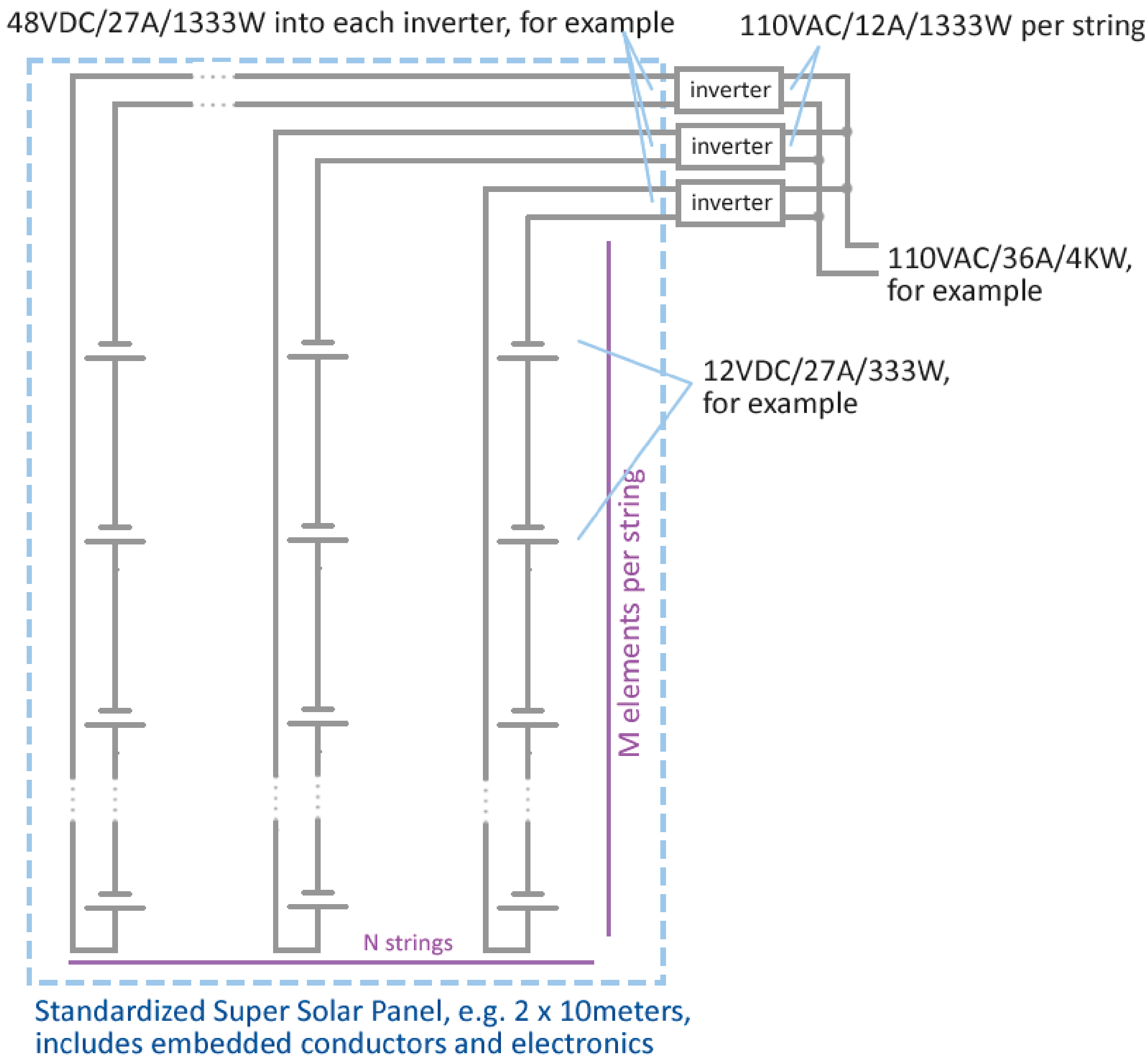
- Electronics are more serviceable due to being outside of panel.

Disadvantages

- Total current is limited by lowest performing cell

Ec2: MULTIPLE STRINGS, NO ELECTRONICS IN PANEL

Similar to previous case, yet multiple strings. No electronics in panel.



Advantages

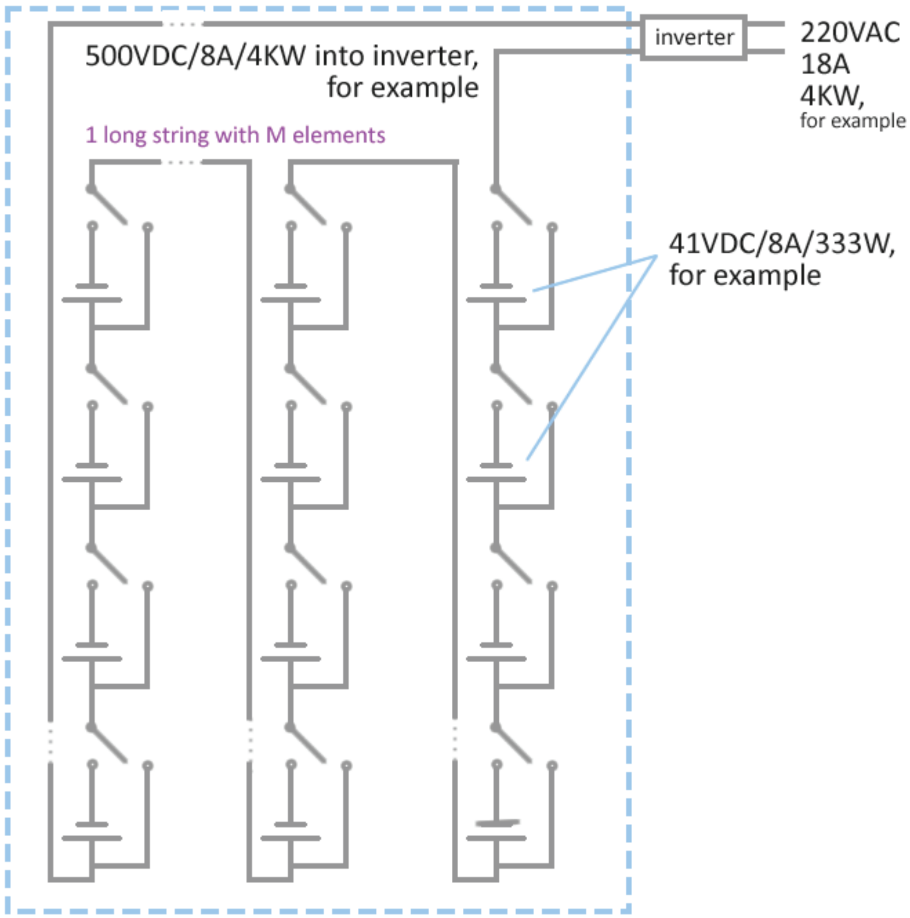
- Electronics are more serviceable due to being outside of panel.

Disadvantages

- Total current is limited by lowest performing cell, within each string.

Ec3: ONE LONG STRING WITH BYPASS SWITCHES AT EACH ELEMENT

One long string of cells with bypass switches for underperforming cells.



Standardized Super Solar Panel, e.g. 2 x 10meters, includes embedded conductors and electronics

Advantages

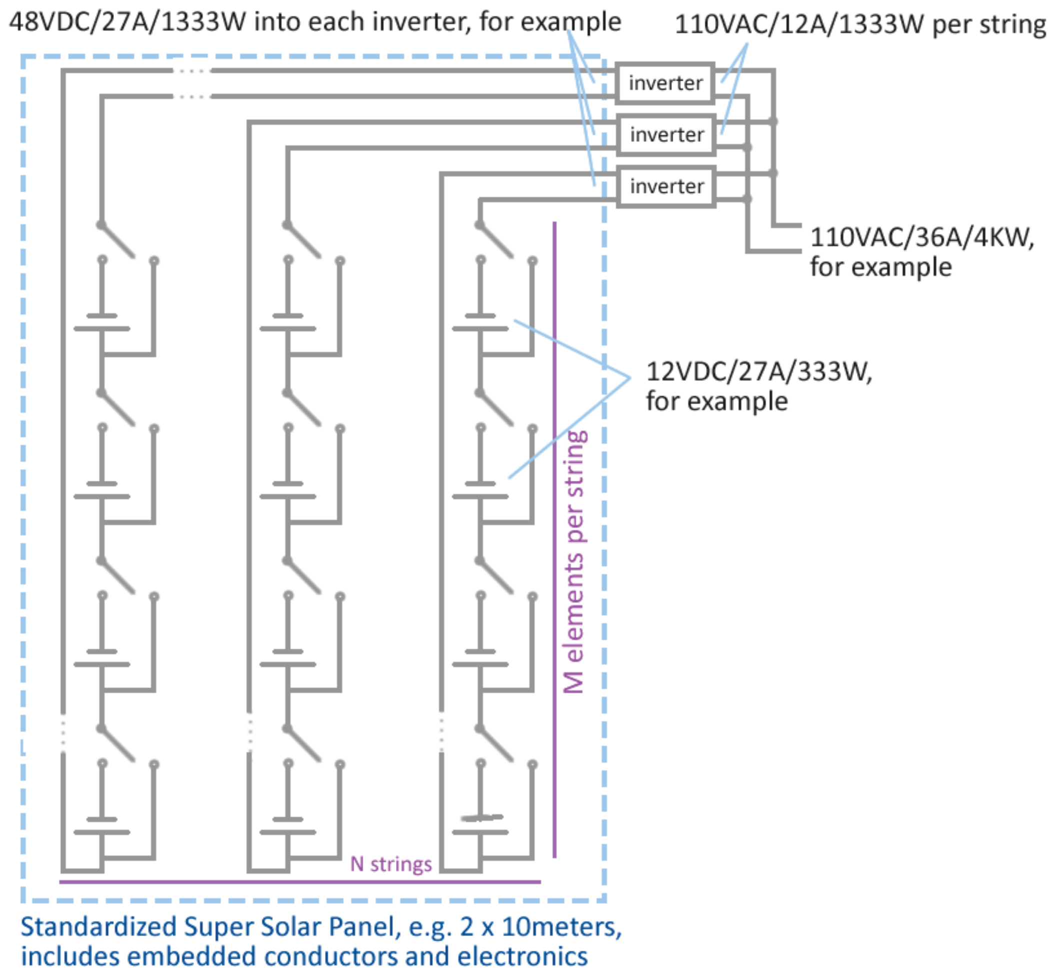
- Bypass underperforming cell.

Disadvantages

- Switches involve costs and energy loss (e.g. voltage drop across MOSFET).

Ec4: MULTIPLE STRINGS WITH BYPASS SWITCHES AT EACH ELEMENT

Similar to previous scenario, except supports multiple strings. Current source inverters combine nicely in parallel.



Advantages

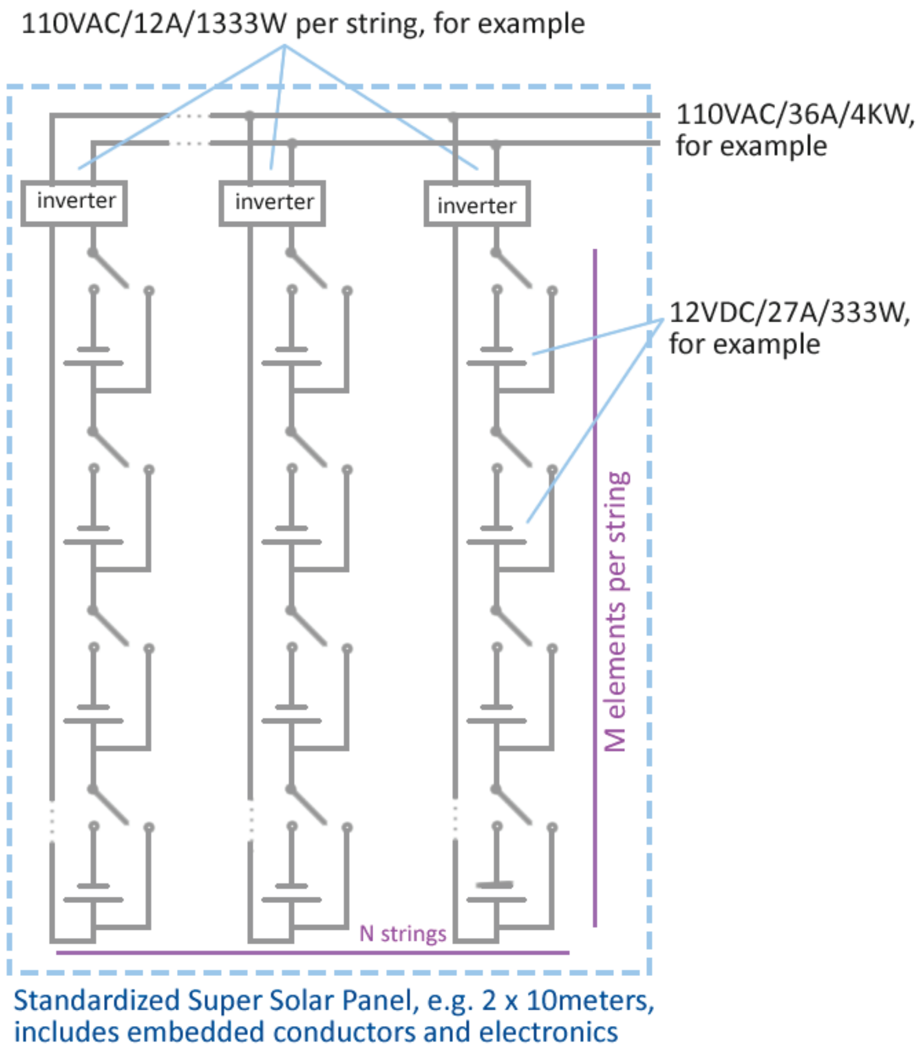
- Bypass underperforming cell.

Disadvantages

- Switches involve costs and energy loss (e.g. voltage drop across MOSFET)

Ec5: MULTPLE STRINGS COMBINED VIA EMBEDDED MICRO-INVERTERS

Similar to above, yet micro-inverters are embedded into panel. Current source inverters combine nicely in parallel.



Advantages

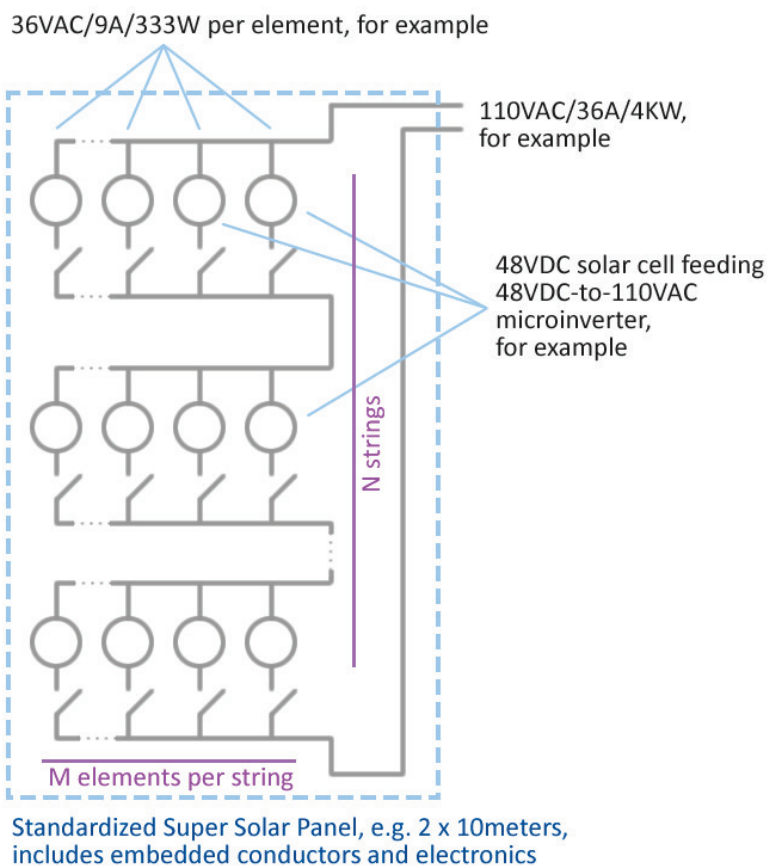
- Bypass underperforming cell and includes micro-inverters.

Disadvantages

- Switches and micro-inverters involve costs and energy loss.

Ec6: CONVERTERS IN PARALLEL AND SERIAL

M elements are wired in parallel to form one set, and then N sets are combined in series. Each element features a solar cell that drives a microinverter (DC-to-AC converter) or optimizer (DC-to-DC converter). N and M can each be 1. In some cases, one might want to work with lower voltage converters that are strung together in series to create higher voltages. Spreading out many converters is one technique for distributing heat and maintaining lower temperatures. Current source inverters combine nicely in parallel, yet not in series. Getting the below circuit working properly is a bit tricky.



Advantages

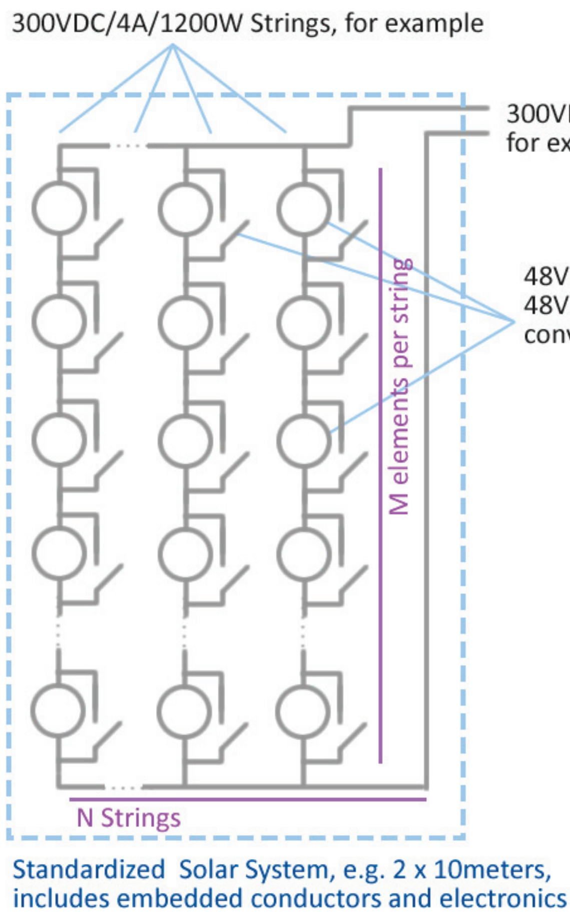
- Easily maximizes power output given degraded cells.

Disadvantages

- More electronics involves more cost.

Ec7: MULTIPLE STRINGS IN PARALLEL

M elements are wired in series to form one string, and then N strings are combined in parallel. Each element features a solar cell that drives a microinverter (DC-to-AC) or optimizer (DC-to-DC converter). N and M can each be 1. In some cases, one might want to work with lower voltage converters that are strung together in series to create higher voltages. Spreading out many converters is one technique for distributing heat and maintaining lower temperatures. This topology is used in our previous Chapter "DC-to-DC Optimizers Embedded into Solar Material"



Advantages

- Easily maximizes power output given degraded cells.

Disadvantages

- More electronics involves more cost.

Ec8: PROGRAMMABLE VOLTAGES

Cells are placed into String-A or String-B, under processor control. This enables one to use switches to build sinewaves and residual waveforms. Subsequently, one can provide AC and/or DC power with programmable frequency and amplitude.

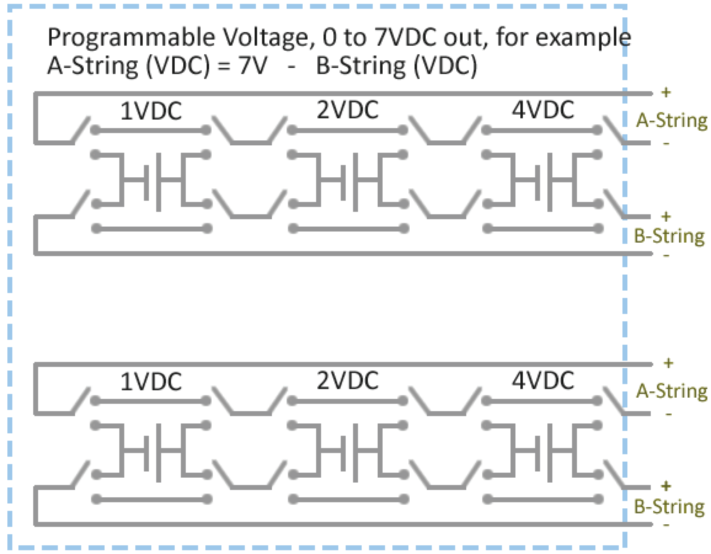
This requires more consideration to determine feasibility.

Advantages

- ?

Disadvantages

- ?



Standardized Super Solar Panel, e.g. 2 x 10meters, includes embedded conductors and electronics