A Quantitative Comparison of Central Inverters and String Inverters in Utility-Scale Solar Systems in North America

System designers have more options today than ever before when architecting solar systems. While this may seem like a great advantage, these options necessitate an ever-growing number of decision points in the design process. There are decisions on system voltage (1000V or 1500V?), racking (fixed tilt or tracking?) and so on… Each decision has implications on cost, performance and serviceability, and it's essential to weigh all these choices before crating the final system design.

No decision has more impact on system cost and performance than the choice of inverters as this dictates design constraints for so much of the balance of system. Before selecting brand or model the designer must first choose the macro level class of inverters, central or three phase string inverters. Until recently, the normalized price of string inverters (as measured in $/W) was much higher than central inverters, making the decision to use central inverters for utility-scale quite straightforward. That unit price gap has greatly diminished, resulting in a heightened debate on the relative merits of central and string inverters, often without empirical data to support the arguments. The jury is still out on which is the so-called "best solution" and likely for good reason as the overall system size has such a significant impact on the relevant answer.

This paper analyzes the relative merits of central and string inverters in a typical system in North America. In specific "typical" refers to the following characteristics:

- The system is rating is ≥10MW.
- The project is located near good access roads that can support 18 wheelers and crane traffic.
- There are skilled service technicians in the area such that getting to the site is straightforward and inexpensive.
- The terrain is relatively flat so that modules in each string and one string to another can be kept in plane without special racking.
- There is an insignificant level of uneven module shading throughout the array.
- There are complex grid codes and grid support requirements for the system.

This analysis is limited to the relative merits of central and string inverters for utility-scale projects in North America. Five key metrics over the life of a system are analyzed:

1. Basic performance requirements of utility-scale projects
2. CAPEX (labor and materials)
3. System operating efficiency
4. Inverter service life
5. True cost of service

It should be noted that the conclusions drawn herein are valid only for utility-scale systems in North America and the reader is cautioned from extrapolating the data and conclusions included herein into other market sectors and/or geographical regions.

Basic Performance Requirements in Utility-scale Projects

Central Inverters	String Inverters
≥2MW per inverter (mechanized lift)	<100KW block size (2-man lift)
Transformerless, typically with non-standard AC voltages	Transformerless, typically with standard AC voltages(380V/400V/480V)
Field serviceable to maintain operating life	Not field serviceable
Typically a grounded design	Typically a floating design
5-year warranty, typically with parts and labor	10* year warranty, typically with parts only
Typically single MPP per inverter	One or multi-MPP per inverter

* Note a standard 10-year warranty is valid in US and Canada, typically 5 years for the rest of the world.

For the purposes of this analysis utility-scale systems are a minimum of 5MW and the entire array is contiguous. We are not considering distributed systems or subsystems distributed in multiple locations. Some of the most common performance requirements of these projects are:

- Interconnects at Distribution Voltages (12.47 – 34.5KV) or Transmission Voltages (42 – 230KV)
- Need for grid support functions requiring voltage regulation and VAR support
- Requirements for Low Voltage Ride Through (LVRT) and/or High Voltage Ride Through (HVRT)

In looking at these requirements a clear trend begins to arise. The grid support functions require closed loop controls via Power Plant Control (PPC). From a communications architecture perspective, central inverters are much easier to coordinate with PPC, having fewer inverters to communicate to, and having the ability to utilize fiber optics instead of copper between the inverters. The ability to use fiber optic communication cost effectively is dependent on the central inverter architecture, and well suited to the data bandwidth and reliable communication needs for both monitoring & control of a utility-scale system. Another central inverter performance advantage is their capability to deliver superior VAR support. String inverters are typically limited to +/- 0.8 PF while central inverters offer power factor over a much wider range.

Centrals also have superior ride through capability typically allowing 1.3 – 1.4PU for high voltage ride through (HVRT), while most string inverters are capped at 1.1 or 1.2. In addition, most central inverters have complex ride through curves that can be programmed, while string inverters come with a very limited number of points of adjustability, typically just one or two, which makes it difficult to coordinate with complex grid interconnect requirements.

CAPEX

The first metric typically used by all designers to make decisions on system architecture is the initial CAPEX cost. The reality is that such an analysis is more than simply a comparison of the relative prices of the inverters. It requires a comparison of the relative costs of the AC and DC BOS as well. One can assume that the all-in costs of modules and racking will be identical and are therefore excluded from this analysis which compares a system comprised of 2MW central inverters with a system built with

60kW string inverters on a 1000V project in North America. The CAPEX analysis is separated into two parts, labor and material.

CAPEX Labor Analysis

Different locations have different fundamental labor rates, and within a single location varying tasks can be performed by staff that have different labor rates as well. In consideration of these challenges, this analysis first limits the discussion to labor hours thereby allowing the reader to make their own precise conclusions in terms of labor cost. Then a monetized comparison is made with a representative labor rate.

The small footprint of string inverters makes them faster to install than central inverters. However, when this small number is multiplied by the sheer volume of units required, a very different picture emerges. To see this more clearly the absolute hours per item are shown (categories of labor cost associated with each type of inverter) and those figures are then used to drive the labor required to build a 20MW block (minimum utility-scale system size) to see the relative labor on a system level in very clear and tangible terms.

Labor Analysis of a 20MW Block Utilizing 2MW Central Inverters vs. 60KW String Inverters

ITEM	CENTRAL		STRING		COMMENT
	hrs/unit	hrs/20MW	hrs/unit	hrs/20MW	
Mechanical installation	14	140	2	667	Skid vs loose string inverter
Electrical installation	35	350	4	1,320	Skid vs string with 7.5min/connection with MC4/H4
Commissioning	4	40	0.25	83	
Inverter Foundation	20	200	1.5	500	Gravel bed for centrals Post and strut for string
DC BOS	112	1,120	0	0	8hrs per combiner box
AC BOS	0	0	1.8	600	Calculated per 2 MW for string and divided by 33 units: 3 hrs per 400A MLO panel 16hrs per large 4000A MCB panel 20 hrs per MVT
TOTALS	**185**	**1,850**	**9.8**	**3,170**	

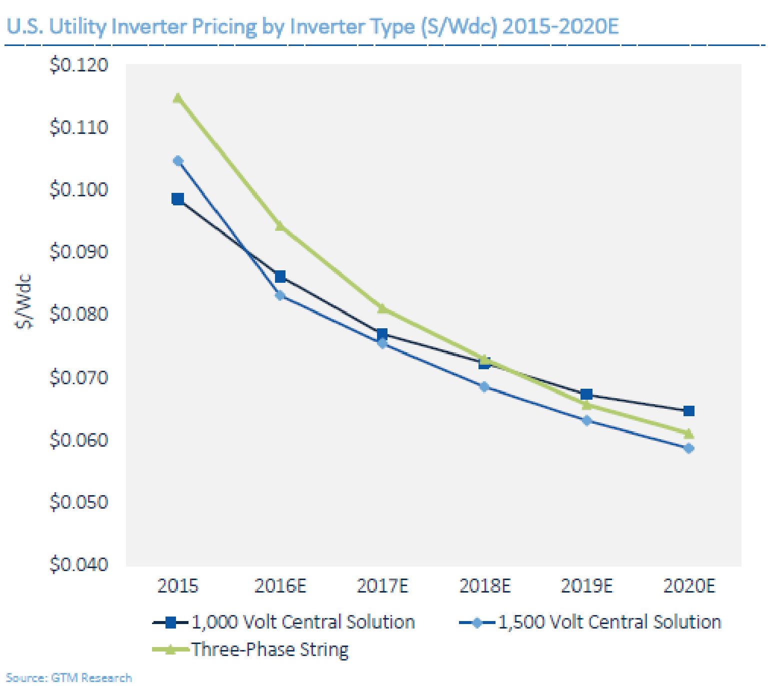
This table shows that while one 2MW central inverter skid and associated BOS takes about 19 times as long to install as a single 60KW string inverter and associated BOS, the fact that there are 33 times as many string inverters to install results in string inverters requiring over 1.7 times the labor to construct a 20MW system building block. This ratio would hold exactly in proportion in larger systems above 20MW without upper bound in system size and is a considerable delta in labor required that is often significantly underestimated.

Monetizing this difference at a conservative fully loaded labor rate of $40/hour results in an increase in labor costs as follows:

(1,320 man-hrs x $40/hr)/20MW = 0.3 ₵/W

CAPEX Material Analysis:

There is a spread of inverter prices in the market and GTM Research's assessment of inverter market pricing shows that string inverters are expected to be priced 0.5₵/W higher than central inverters in U.S. utility systems (see figure below). When considering the rest of the material costs, there is absolutely no question that a system using string inverters will have lower DC BOS cost, as the inverter itself is the only piece of DC equipment required and the inverters are placed much closer to the modules. A more complete analysis discloses that these DC BOS savings are more than canceled out by a significant uptick in AC BOS costs.



Comparison of Material Costs of Utility-Scale Systems Utilizing Central and String Inverters

ITEM	CENTRAL	STRING	COMMENT
Differential Cost per Inverter (₵/WAC)	7.6	8.1	Both configured with DC disconnect and DC fuse protection. Centrals include AC protection, strings do not. Strings include AFCI.
Incremental Cost to Skid (₵/WAC)	2.5	N/A	Centrals include integration labor for power block, auxiliary power, foundation slab and MV Transformer.
DC BOS per Inverter (₵/WAC)	0.8	N/A	Based on 400A combiner boxes, 14 per 2MW. Both systems designed for 1% DC cabling losses.
DC collection per Inverter (₵/WAC)	2.0	0.4	Based on comparable 1.4 DC Ratios.
AC BOS per Inverter (₵/WAC)	N/A	3.0	String inverter includes MV Transformer, AC MLO combiner panel and MCB recombiner panel. Central included in skid price.
AC collection per Inverter (₵/WAC)	0.2	3.5	Based on 1% voltage drop max for string, Based on NEC min ampacity table for centrals.
Totals (₵/WAC)	**13.1**	**15.0**	A utility system using string inverters requires an incremental CAPEX investment of 2.4₵/W.

This analysis shows that a system constructed with 60KW string inverters will require 1.9₵/W more in CAPEX material than a system built with 2MW central inverters. This is a significant difference in CAPEX. If the 0.3₵/W increase for labor is added to this 1.9₵/W for material, then string inverters require 2.2₵/W more in CAPEX in utility-scale systems.

System Operating Efficiency:

The key differentiator in considering system efficiency is the losses in the AC and DC portions of the system as the inverters essentially have the same efficiency. The material and labor costs in the previous section were based upon the premise that limiting DC losses to 1% is good design practice. In this analysis, there is therefore no difference in DC losses as they are both driven to 1% by cable sizing. Losses in the MV AC cabling is negligible and are therefore not included in this analysis. The discussion is therefore limited to the relative AC losses in the two systems, excluding MV losses, as this is the only differentiator.

Analysis of AC Losses in a 20MW Block Using 2MW Central Inverters vs. 60KW String Inverters

ITEM	CENTRAL	STRING
AC Connection	2MW AC @ 575V	2MW AC @ 480V
Transformer Coupling	Close coupled to AC transformer	Max distance 505 ft to transformer
Max Conductor	Nonmaterial due to close coupling	3/0
AC Losses	0.15%	1.0%

AC losses for central inverter systems are driven by minimum design requirements as dictated by code. For string inverter systems, AC losses are dictated by performance losses and limitations of inverter physical wire management, and 1% is a good practice and is achievable. There are therefore 0.85% more electrical losses in a utility-scale system designed with string inverters than with central inverters.

Inverter Service Life:

Utility-scale PV plants are generation assets that are expected to provide a financial return over at least 20 years. A PV plant must therefore operate predictably over that period. Service life of the inverters is therefore a critical consideration in selection of string or central inverters.

Central inverters meet this requirement for service life as all major suppliers offer products with at least a 20-year service life. There has also been a shift of late to higher service life of 25 and even 30 years. The appropriate service life for utility-scale systems is achieved through a proactive service and maintenance program. This strategy has been proven time and time again over the years in utility-scale installations worldwide. Service contracts with limits on downtime are typically available from highly bankable suppliers. This effectively takes all the risk out of OPEX calculations.

Service life is not nearly as straightforward when considering string inverters. First, string inverters do not have published service life like central inverters. Field service and maintenance of string inverters is relegated to a combination of replacing a few basic components, such as LCD screens, and in some cases fans, if the core components are still functional. Removal and replacement (so called “rip and replace”) of inverters is required if a unit can no longer process power.

Thus, many investors include the cost of a full replacement of all string inverters at the end of the warranty period in their financial calculations, but this assumes there will be replacements available with compatible specifications. That is where the issue becomes even more murky. If past is prologue, then there is a very serious likelihood that there will not be an equivalent form/fit/functional replacement available 10 or 15 years from the date of initial purchase. Imagine trying to find such a replacement today for string inverters installed in 2006. The recent decade of evolution from 600V to 1000V and now to 1500V puts more doubt on the availability of backwards compatible inverters at a reasonable cost over a decade from now. This means that the true replacement and installation cost of out of warranty failed string inverters is essentially indeterminate.

Future inverter replacements and backwards compatibility challenges:

The biggest risk from a technical perspective when using string inverters commonly available on the market today is that inverters available in the future may not match the DC voltage of the PV array. Solar panels purchased with a given DC voltage rating cannot be re-wired for higher voltages down the road. Even if they could, a complete array re-wiring to change the string configurations would be prohibitively expensive. Finding a solution for DC compatibility may require exploration of custom or niche inverter products or DC/DC converters which would typically be 2x to 5x the cost of mainstream inverter products.

Once a solution for DC voltage compatibility is found, there are several other factors in determining inverter backwards compatibility and the expense for the replacement. If inverter power ratings are not equivalent, some re-wiring on the DC side will be required. If the AC voltages are different, there will need to be an additional transformer installed or a replacement of existing transformers. If the form factor of the inverter is different, there may need to be adjustments to the foundations or mounting structure to accommodate the new unit.

Financial Exposure from Future Replacement of String Inverters

Item	Cost (₵/W)
Custom inverter and/or DC/DC converter + wiring	20 - 50 ₵/W
Electrical re-work to match DC home run strings to new inverter power ratings	2 - 3 ₵/W
Transformer installation (materials and installation)	3 - 4 ₵/W
Foundation or mounting structure adjustments	0 - 1 ₵/W
Total risk exposure	**25 - 58 ₵/W**

Note that these risks are often ignored when during the decision process to use string or central inverters is made even though these figures would decimate the financial return of a system if suitable replacements were not available in the future. The bottom line is that in contrast to central inverters where service contracts with uptime guarantees are available from bankable suppliers, the service risk and future service cost of string based systems is essentially indeterminate.

True Cost of Service

There is a common misconception that the cost of service in a utility-scale system built with string inverters is negligible. This turns out not to be the case as is quantified in this section. The true cost of service is measured by first defining an operational performance goal, then implementing a maintenance regime that addresses the planned and unplanned servicing of the equipment. Comparing true service costs of 2MW central and 60KW string inverters is challenging as warranties are structured for different durations in North America, (5 years for central vs 10 years for string) with different terms (parts and labor vs parts only).

A comprehensive 20-year service contract for a 2MW central inverter can easily be secured for the selling price of that inverter, equating to an average cost of 7.6₵/W per the market price data from GTM Research as previously sited translating to $152K over 20 years, or $7.6k per year as the OPEX cost for a typical 2MW inverter. This includes planned and unplanned O&M, parts and labor as well as an uptime availability guarantee. An uptime guarantee in conjunction with a service contract from a bankable supplier bounds future OPEX costs for that inverter to a specific number while also bounding the downtime, or lost energy due to failures. This effectively removes all financial unknowns and risk from inverter OPEX estimation in the project financial analysis.

For string inverters, the calculation is more complex and one must account for 2 scenarios, inverters under warranty, so labor the owner would need to bear the labor costs of removing and replacing these units, and inverters out of warranty where the owner would also be responsible for the inerter cost as well. Using current industry metrics for failure rates, average fleet will see failures in the 3% range each year for the first ten years. This equates to one unit failing per year of the thirty-three 60KW string inverters installed in each 2MW block (3% of 33 inverters in the 60KW block). In year 11 there is a decision point to replace the entire population of inverters or continue to replace as failures occur. If the units are not replaced, then the failure rate will increase dramatically in years 11 to 20. This analysis doubles the failure rate to 4% in years 11 through 15 and 5% in years 16 through 20.

The cost of a truck roll plus labor for tear out and replacement starts at $750 and will cost $1008 in year 11 and year $1168 in year 16 allowing for a 3% escalation per year. In addition to the truck rolls due to replacements of failed units, there are also truck rolls for other items such as firmware updates, nuisance trips, fan replacements and LCD replacements. This analysis conservatively assumes one such truck roll per quarter for the first ten years, one every other month in years 11 – 15, and 3 every 4 months in years 16 – 20 in the absence of a replacement of all inverters in year 11. If all inverters are replaced in year 11 then these other truck rolls are assumed to remain at the rate of 1 per month for the duration of the project. The cost of a replacement 60KW inverter is assumed to be $4200.

Service Costs Over a 20 Year Life for a 2MW Building Block Using 60KW String Inverters

			Replace Only When Fail			Replace All In yr 11		
	Truck Roll + LOH	Failure Rate	Fail/yr	Other Truck Rolls	Cost	Fail/yr	Other Truck Rolls	Cost
Year 1 - 10	$750	3%	1	4	$37,500	1	4	$37,500
Year 11 Replacement					$0		3	$141,624
Years 11 - 15	$1,008	4%	2	6	$82,317	1	4	$25,198
Years 15 - 20	$1,168	5%	2	9	$106,266	1	4	$29,212
TOTAL ($)					$226,084			$204,322
TOTAL (₵/W)					11.3			10.2
Delta to Central 2MW					$74,084			$52,322
Delta to Central ₵/W					3.7			2.6

In both cases the lifetime service cost is considerably higher for the string inverter system than it is for the central system and ranges from about 10₵/W to 11₵/W. Of these two options the replacement of all inverters in year 11 clearly provides a far better lifetime cost than rolling the dice on the installed inverter population for the full 20 years. This therefore debunks the myth that the lifetime cost of service on a string system is cheaper than central systems, much less negligible in the absolute sense. It is important to keep in mind that both scenarios as presented above assume the availability of form/fit/functional replacements 10 to 20 years after construction when such has clearly not been the case to date. If that turns out not to be so, then the project will take a 25₵/W to 58₵/W hit as shown earlier in this analysis.

Atypical System Considerations

As stated previously this paper analyzes the relative merits of central inverters and string inverters in typical utility-scale systems in North America. There are of course atypical systems that do not fit this mold and the conclusions can be very different for such systems.

1. System is rating below 5MW.
    a. Using 2MW central inverters in a system below 5MW may result in purchasing significant excess capacity simply because of the multiples of the fundamental building block. For instance, if a system is 3MW then one would use two (2) 2MW inverters. One would be derated by 50% to 1MW, so 25% of the total purchased inverter capacity would be unutilized, significantly increasing the delivered ₵/W of these 2MW central inverters. The best solution will depend upon system rating, available inverters, OPEX considerations and any other atypical characteristics as well.

2. The project lacks good access roads and/or no cranes available.
    a. Simply put if you can't get central inverters skids or inverters themselves on site, or place them in the array once they arrive on site then string inverters are an excellent choice and in fact the only possible choice for such locations.
3. Skilled service technicians are not available in the area and getting them to the site is complicated and expensive,
    a. Field service of central inverters requires a skilled service tech to visit the site while the rip and replace service strategy for string inverters requires a much lower skill level service technician. Therefore, string inverters are the best choice for projects where it is impossible to get a skilled service technician on site.
4. The terrain is highly irregular so and strings are not in plane with each other.
    a. In such cases the increased granularity of MPPT in string inverters will compensate for some of this mismatch, where central inverters will not. The complete financials of the project must be examined, but string inverters may well be the best solution in such cases.
    b. Some projects have a portion of the site that is level and other portions that are irregular. In such cases the best solution may be a combination of central and string inverters.
5. There is an insignificant level of <u>non-uniform</u> module shading throughout the array.
    a. Here the answer is the same as in # 4 above, the increased granularity of MPPT in string inverters will correct for some of this mismatch. Project economics must be analyzed and string inverters are attractive because they will correct for some of the mismatch caused by uneven module shading.

Conclusion

This quantitatively analyzes the merits of using central inverters and string inverters in typical utility-scale solar systems in North America. Results were quantified in the following key decision criteria:

- Performance
    - Basic performance requirements of utility-scale projects
    - System operating efficiency
- Cost
    - CAPEX (labor & materials)
    - OPEX
        - Inverter service life
        - True cost of service

While three phase string inverters clearly have their place in the market, this study shows that central inverters are far and away the superior choice for typical utility-scale projects in North America. String inverters become much more viable in the face of certain project challenges such as poor access roads, lack of skilled service teams in the region and non-uniform mismatch due to uneven terrain or shading

Central inverters showed significant measurable advantages over string inverters in every aspect of the analysis. The ability of central inverter systems to provide superior VAR support, LVRT and HVRT meets the performance requirements of even the most challenging utility-scale installations where string inverters fall short. Central systems are almost 1% more efficient end to end. From a financial perspective, central inverters are a more attractive investment.

The CAPEX advantage of 2.2₵/W makes central inverter systems a more prudent initial investment. In addition, OPEX in central inverter systems is 2.6 – 3.7₵/W lower than string inverter systems over system life, and the possibility of a 25 - 58₵/W expenditure looming in the future the OPEX advantage is potentially disastrous. Lastly, fact that one can readily purchase a service contract for central inverters with availability guarantees from highly bankable suppliers eliminates all financial risk with respect to inverters for the life of the system. Central inverters are therefore the logical choice for a long-term investment in a utility solar generation asset in North America.