Performance and Techno-Economic Evaluation of a Three-Phase, 50-kW SiC-Based PV Inverter

Preprint

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National Renewable Energy Laboratory

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Performance and Techno-Economic Evaluation of a Three-Phase, 50-kW SiC-Based PV Inverter

Akanksha Singh, Samantha Reese, and Sertac Akar

National Renewable Energy Laboratory, Golden, Colorado, 80401, USA

Abstract — **The technical capabilities and benefits of silicon carbide (SiC) compared to silicon (Si) based power electronics converters as well as the premium associated with using SiC instead of Si are well understood. This work proves that the benefits provided by SiC, such as increased efficiency, would result in a lower levelized cost of energy (LCOE) compared to both commercially available, state-of-the-art inverters and the benchmark commercial system cost calculated for the U.S. Department of Energy Solar Energy Technologies Office's SunShot program. The LCOE is calculated to be same as the commercial benchmark despite the installed system cost being 8% more than the benchmark. The LCOE calculation is based on both experiential values obtained from testing the SiC photovoltaic (PV) inverter and on the bottoms-up modeled volume cost for the same 50-kW SiC-based inverter. The PV system used for the LCOE model is also explained, and the system cost breakout is presented in this paper. Furthermore, multiple scenarios with variations in the PV system are presented to show their effect on the system LCOE.**

Index Terms— **Levelized cost of energy, SiC converters, techno-economic analysis, wide bandgap converters.**

I. INTRODUCTION

The technical capabilities and benefits of silicon carbide (SiC) compared to silicon (Si) based power electronics have been quantified to a large extent. The purpose of techno-economic modeling of the SiC-based inverter is to determine the minimum sustainable price (MSP) at which the inverter could sell if the inverter were manufactured in quantities consistent with current inverter manufactures. Furthermore, such analysis helps determine if the increased costs associated with wide-bandgap devices, specifically SiC, could be overcome by the increased performance enabled by SiC capabilities. In [1], Horowotiz et al. demonstrated, through a bottoms-up model that the savings from space and cooling in a SiC-based 1-MW variable-frequency drive resulted in an overall drive cost similar to the current industry standards. In order to understand and judge the cost benefits associated with the proliferation of wide-bandgap based photovoltaic (PV) inverters, it is necessary to model their MSP as well as determine the levelized cost of energy (LCOE) if such inverters were to be used in widespread grid integration of PV systems.

This work proves the benefits of SiC, including increased efficiency resulting in a reduced LCOE, even with the increased system cost. The MSP calculated from the techno-economic analysis (TEA) shows the breakeven price the inverter could sell for without the company taking a loss. This is not the market price. Having determined the inverter costs, the second part of this work couples cost data with the tested efficiency curves for the developed inverter prototypes and determine the LCOE. The premise is that even if they are sold at a slightly higher cost than current inverters, the performance gains realized from the SiC would enable the LCOE to be reduced. The LCOE calculation is based on experimental values obtained from testing the SiC inverter and the bottoms-up cost model for an actual developed 50-kW SiC-based PV inverter. In this paper, the cost analysis, inverter performance data, and LCOE analysis of a three-phase, 50-kW, 480-V, SiC-based, single-stage, two-level PV inverter is presented. Section II elaborates on the bottoms-up cost modeling of the SiC inverter, which covers cost of switch module development from bare die. The high-volume cost of the inverter is modeled, and the concept of the minimum sustainable price is further explained, in this paper. Additionally, the power module cost is modeled using current die pricing as well as future die pricing. The inverter performance is quantified and presented in Section III. The inverter is then embedded in a PV power plant based in Phoenix, AZ, and the LCOE from the power plant is presented in Section IV. The LCOE for this PV system is compared with a similar PV plant developed using a Si-based, state-of-the-art inverter, and the results are presented in Section IV. The conclusions of the presented work is summarized in Section V.

II. BOTTOMS-UP COST MODEL

Bottoms-up cost analysis provides quantitative insights into areas that will be most impactful if advancements are made. The bottoms-up cost model considers individual elements of the manufacturing costs and overhead costs, which are analyzed as cash flows during the life of the manufacturing facility. The model includes cost categories associated with manufacturing such as material, labor, utilities, maintenance, and capital costs [2]. The methodology used to produce the models helps predict the MSP at future levels of manufacturing. The MSP is the cost at which the product must be sold to pay back all capital and operating investments during the plant lifetime. This helps assure technology adopters that once a technology becomes

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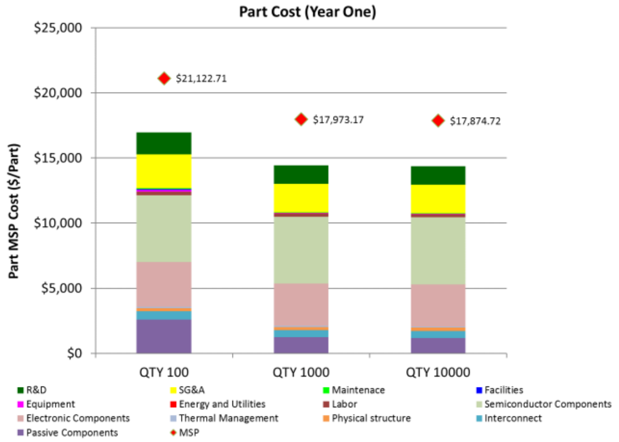


Fig. 1: Modeled factory gate pricing of Alpha SiC inverter

commercially available and is produced in larger volumes, there is a path forward for price reduction. It conservatively assumes that all equipment and components are purchased new at full price. Process-specific input data—e.g., labor cost, throughputs, utility usage, material pricing—are collected from industry members, material suppliers, equipment manufacturers, and market reports. The model assumes that the equipment and factory space is dedicated to inverter manufacturing and not used for other purposes. Furthermore, it uses U.S.-based factors, such as labor, taxes, borrowing rate, and anticipated payback.

The individual inverter parts are all treated as purchased parts in the model except for the power block made from SiC devices. The cost modeling of two different versions of SiC-based PV inverters are analyzed. The first model is for an inverter developed from commercially available 1700-V SiC MOSFET modules and gate drivers, hereby known as the Alpha inverter. The second model is for an inverter developed from in-house-developed SiC modules from bare dies and gate drivers with optimized heatsinks, hereby known as the Gamma inverter. The bill of material of the Alpha inverter and the TEA methodology described previously are used to model the anticipated cost of the inverter in various production volume scenarios. The volumes are based on an evaluation of the solar inverter suppliers. The approximate volume of manufacturing is determined for the bottoms-up cost modeling using data in [3]. Fig. 1. The figure shows the modeled MSP for the Alpha SiC inverter design when manufactured at different volumes.

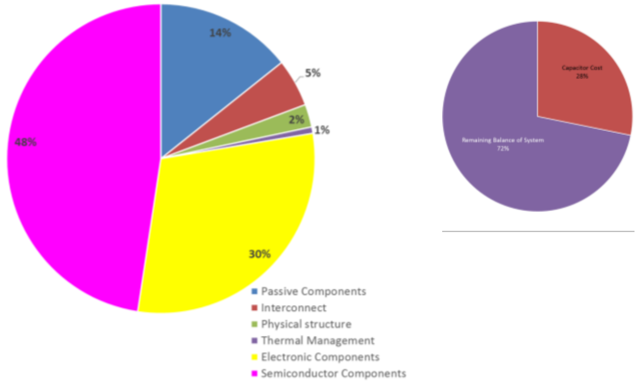


Fig. 2. (Left) Breakdown of SiC inverter material costs, (Right) film capacitor contribution to passive cost.

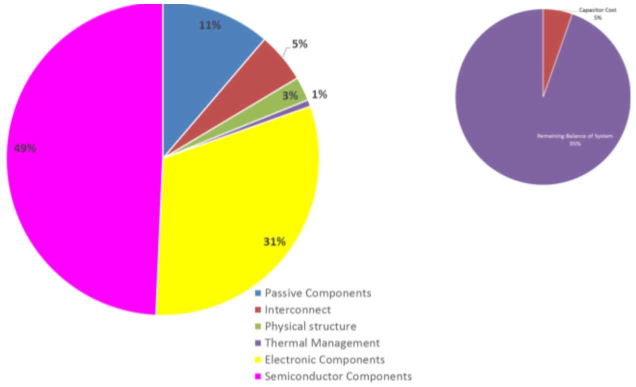


Fig. 3. (Left) Breakdown of SiC inverter material costs, (right) electrolytic capacitor contribution to passive cost.

The main driver in the manufacturing cost is economies of scale from parts procurement. The higher the volume the individual components are purchased in, the lower the overall cost for the inverter. Further, the model assumes that the area used for manufacturing the SiC inverter is dedicated space; thus, the yearly cost for that space is divided by the yearly volume. Ultimately, the cost for the inverter is calculated to be $.36/W.

Electrolytic capacitors used at the dc-bus cause most frequent failures in power converters, and film capacitors have a longer lifetime and higher reliability [4]. Fig. 1 was modeled using electrolytic capacitors. Fig. 2 shows the contribution to the overall material cost of the components when the design is using film capacitors. Passive components contribute 14% to the overall material cost. The film capacitors are 28% of that contribution, which is less than 4% of the total material cost. The design was modified to use electrolytic capacitors to gain understanding of the trade-offs between cheaper components, i.e., electrolytic capacitors and longer life that is expected using the film capacitors. The goal was to identify the per-watt difference between the two designs. The inverter MSP for the design using film capacitors, manufactured at a 10,000/year volume was ~$18,495. If electrolytic capacitors were used in lieu of film capacitors, manufactured at the same volume level, the MSP of the inverter would be reduced to ~$17,874. This represents a ~3.5% cost reduction, which equates to a total of $0.01/W reduction in cost. Fig. 3 shows the material cost breakdown of the design using electrolytic caps. In this scenario, 20% of the material cost is from passive components, of which the electrolytic capacitors are contributing 5%. The overall contribution of the electrolytic capacitors to the material costs is less than 1%; however, electrolytic capacitors are known to be one of the leading causes of power converter failure and result in decreased reliability of the inverter [4],[5].

The second inverter cost modeling is done for the Gamma inverter, which is developed using the SiC MOSFET and diode dies to develop the power module in-house. The power module is developed using dies from CREE and Rohm. The cost modeling for this inverter is done using both current SiC die pricing as well as future die pricing for SiC MOSFETs and diodes. The inverter is modeled at various yearly manufacturing volume levels up to 10,000 per year. The top volume is determined based on market report detailing the volume manufacturing levels of the current top inverter manufactures.

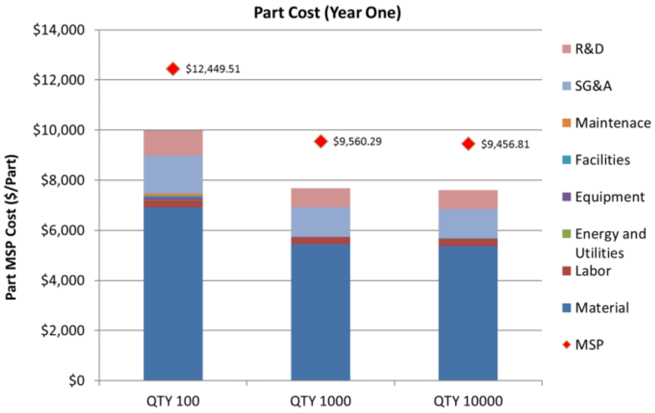


Fig. 5. Modeled factory gate pricing of Gamma SiC inverter using current die pricing.

The volume level of the sixth through tenth top ten inverter manufacturers is used as the determining factor. Fig. 5 shows the MSP for the 50-kW SiC Gamma inverter using the cost of power blocks with current die pricing. The 10,000 per year manufacturing level yields an inverter price of $9,457/inverter. This translates to a $0.19/W price point. The second cost modeling is also completed using the parts from the Gamma inverter design but with the modeled anticipated future cost for a SiC MOSFET and the current Rohm diode pricing. The current Rohm diode pricing is less than the modeled future diode pricing, so it is used instead. The potential pricing of a 3.3-kV SiC MOSFET is modeled in [1]. Even though the Gamma inverter uses 1700-V SiC devices, the majority of the cost is in the wafer, and it was determined that using the future modeled cost of a 3.3-kV MOSFET would be a conservative approximation for a future 1700-V MOSFET. Fig. 6 shows the MSP for a 50-kW SiC inverter based on the Gamma design. The only difference from the first model is that the power block price assumes future die pricing. The total cost is $7,284 in volumes larger than 10,000. This equals a cost of $0.15/W for the inverter.

III. INVERTER PERFORMANCE

The developed three-phase, 50-kW PV inverter uses SiC MOSFETS and diodes as the semiconductor devices in the power block, has new symmetrical Y-core inductors in the ac filter, and has a controller with advanced inverter functions for grid-support functionality. The inside view of the developed PV inverter is shown in Fig. 7. The inverter is tested in stand-alone and grid-tied modes of operation. The grid is formed using Ametek's RS90 grid simulator. The inverter switching frequency for these tests is 20 kHz, and the dc-bus voltage is maintained at about 900 V. The inverter efficiency as measured at different loads with the dc-bus voltage of 900 V is shown in Fig. 4. The peak efficiency of the inverter is computed to be 98.2 ± 0.053%, whereas the California Energy Commission efficiency is computed to be about 97.72 ± 0.05%. It should be noted that the efficiency calculation includes losses in the controller and the thermal management system (fans). This measured efficiency curve is used in deriving the LCOE obtained from the PV system using the developed inverter.

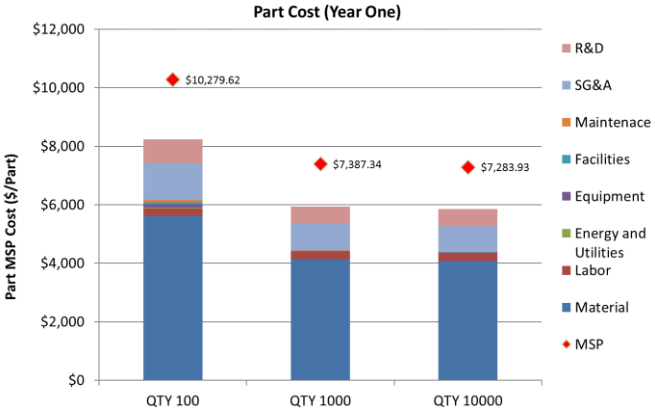


Fig. 6. Modeled factory gate pricing of Gamma SiC inverter using future die pricing.

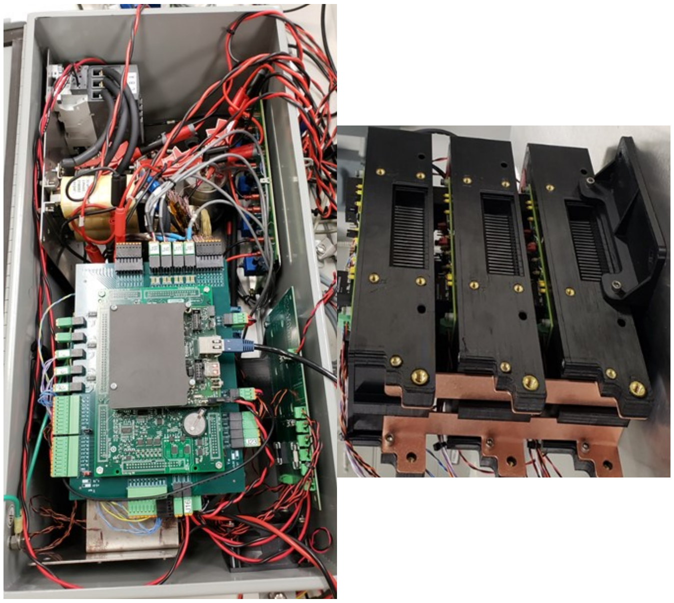

(a) (b)

Fig. 7. (a) Inside view of the developed Gamma three-phase, 50-kW, 480 $V_{LL,rms}$ SiC-based PV inverter, (b) power block of the Gamma inverter.

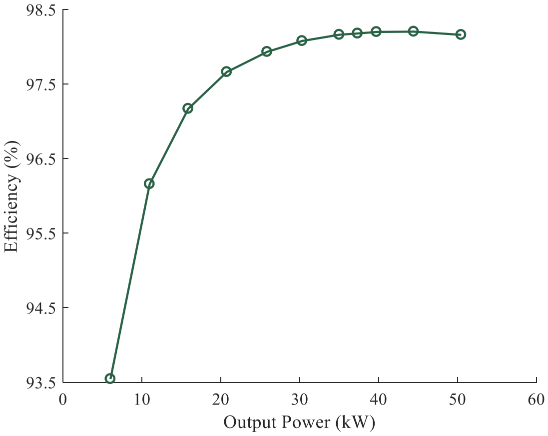
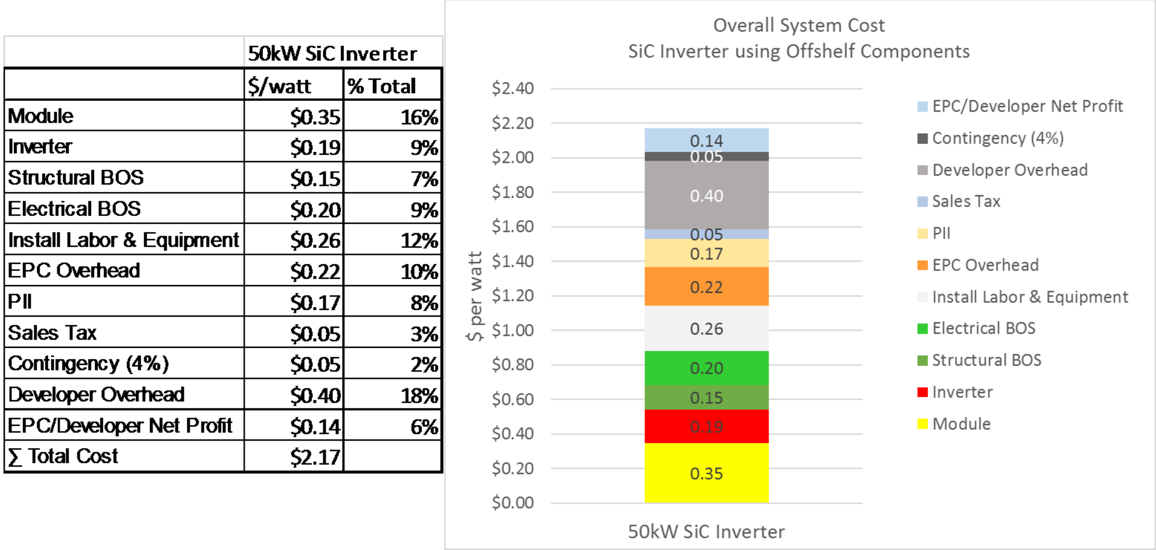


Fig. 4. Measured PV inverter efficiency at different loads.



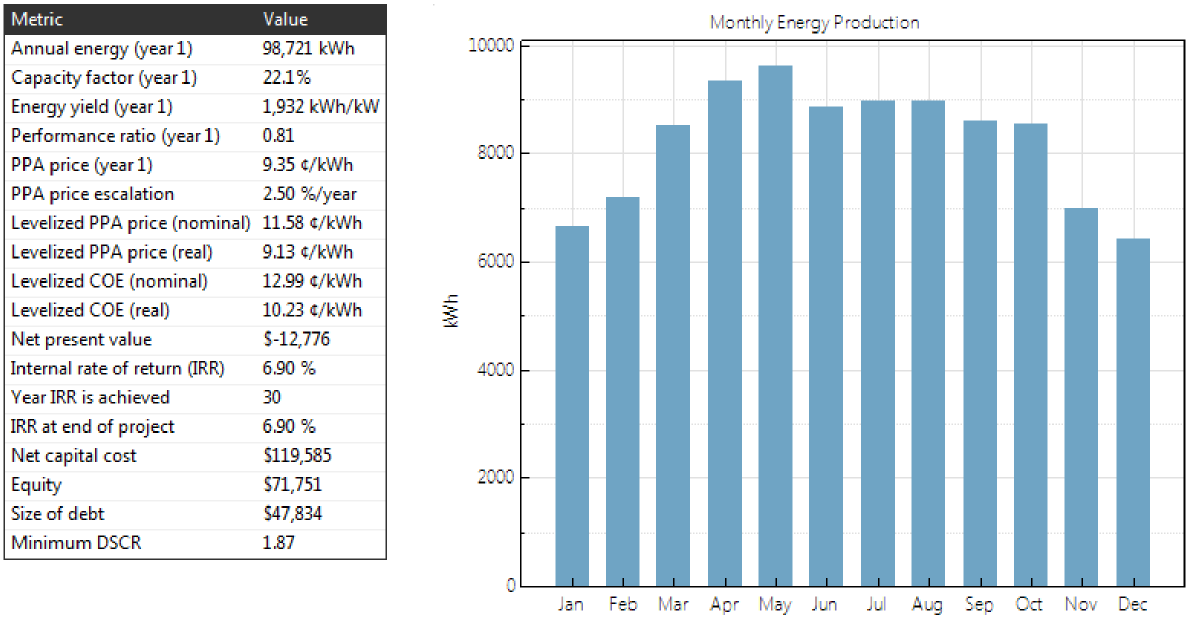
	50kW SiC Inverter	
	$/watt	% Total
Module	$0.35	16%
Inverter	$0.19	9%
Structural BOS	$0.15	7%
Electrical BOS	$0.20	9%
Install Labor & Equipment	$0.26	12%
EPC Overhead	$0.22	10%
PII	$0.17	8%
Sales Tax	$0.05	3%
Contingency (4%)	$0.05	2%
Developer Overhead	$0.40	18%
EPC/Developer Net Profit	$0.14	6%
∑ Total Cost	$2.17	

Fig. 8. PV system cost based on developed SiC-based PV inverter.

IV. LEVELIZED COST OF ENERGY STUDIES

This section first presents the LCOE for a PV system installed in Phoenix, AZ, with Gamma inverter. For this analysis, the current price of the SiC MOSFET dies is used. Next, the results for the same analysis are presented using future die pricing. Both these systems were modeled using thin-film PV modules. The next two analyses using Si PV module with current and future die pricing. Next, the LCOE analysis for a PV system using Si-based, state-of-the-art inverter is presented using thin-film and Si PV modules to compare with the SiC based system.

LCOE is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis and it incorporates performance and lifetime instead of focusing exclusively on first-year capital expenditure. In order to understand the impact of the inverter on the overall LCOE, it is necessary to model a PV system using the inverter. Furthermore, it is important to determine if the LCOE is lower during the lifetime of the system. The US Department of Energy Solar Energy Technologies Office's 2017 benchmark report states the LCOE goals for both 2020 and 2030. The current value and 2020 goal LCOE for a commercial system is $0.09/W and $0.08/W, respectively. In order to calculate the LCOE for a system based on the SiC inverter, the System Advisor Model (SAM) developed at the National Renewable Energy Laboratory (NREL) is used. The same financial assumptions used for the benchmark LCOE calculation are used for the SiC system model [6].



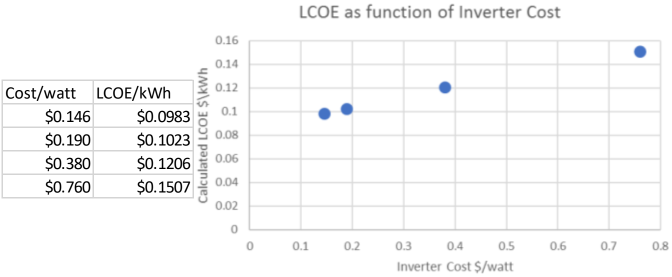
Metric	Value
Annual energy (year 1)	98,721 kWh
Capacity factor (year 1)	22.1%
Energy yield (year 1)	1,932 kWh/kW
Performance ratio (year 1)	0.81
PPA price (year 1)	9.35 ¢/kWh
PPA price escalation	2.50 %/year
Levelized PPA price (nominal)	11.58 ¢/kWh
Levelized PPA price (real)	9.13 ¢/kWh
Levelized COE (nominal)	12.99 ¢/kWh
Levelized COE (real)	10.23 ¢/kWh
Net present value	$-12,776
Internal rate of return (IRR)	6.90 %
Year IRR is achieved	30
IRR at end of project	6.90 %
Net capital cost	$119,585
Equity	$71,751
Size of debt	$47,834
Minimum DSCR	1.87

(a) (b)

Fig. 9. (a) Details of the Gamma inverter LCOE using current die pricing for a PV system installed in Phoenix, AZ, (b) monthly energy production for Phoenix, AZ.

The first step in doing an LCOE calculation is determining the system cost. Fig. 8 shows the total system cost for the SiC Gamma inverter system (the power block price uses current SiC MOSFET pricing), which is a 50-kW system. The PV system modeled here uses thin-film PV modules. This is obtained using the costs identified in the benchmark report and extrapolating to account for the system size being 50 kW instead of 100 kW [6]. The MSP determined using the bottoms-up methodology is used for the inverter pricing. The total system pricing is $2.17/W as compared to the $2.03/W pricing for the 100-kW benchmark system. SAM is the underlying tool used to calculate the LCOE in the SunShot benchmark, and it is used to calculate the LCOE for this case [7]. The model also requires the lifetime of the inverter, the inverter efficiency over the load, which was quantified from the inverter performance and reliability analysis. As noted above, all financial assumptions – such as maintenance, taxes – used for the commercial benchmark SAM LCOE model are used for the SiC system including a 15-year inverter life. Fig. 9(a) shows the results of the LCOE modeling. The current model results, using the MSP for the Gamma inverter based on current MOSFET pricing, shows the real LCOE to be $0.1023/kWh. The PV system modeled used Phoenix, AZ, as the location for energy production data of the year (see Fig. 9(b)), which results in an LCOE of $0.1023/kWh. The resulting LCOE shows that even with the SiC inverter driving the system cost higher, the resulting LCOE is less than the benchmark system [6].

Fig. 10 shows the same system, using the same assumption; however, the inverter pricing is based on the assumed future SiC die pricing. This reduces the LCOE to $0.0983/kWh. This means that even with the increased cost of the SiC inverter, the improved performance makes the lifetime cost on par with current systems. Furthermore, the future die pricing was the only parameter used for developing this LCOE and it does not consider the future performance and life improvement of the inverters. The advancements in the inverter performance will further enable low LCOE for future PV systems.

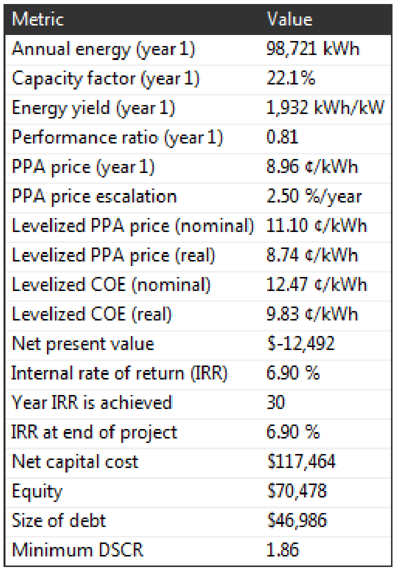


Cost/watt	LCOE/kWh
$0.146	$0.0983
$0.190	$0.1023
$0.380	$0.1206
$0.760	$0.1507

Fig. 11. System LCOE variation as Gamma inverter cost is varied.

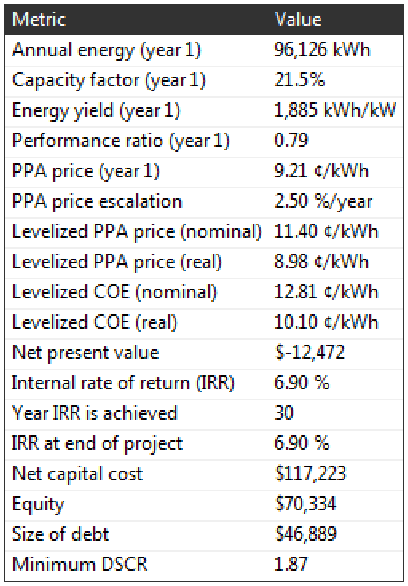
Another aspect quantified in these studies is change in system LCOE with variation of inverter cost. For this study, the LCOE analysis is done by changing the cost for the inverter while keeping all other aspects of the PV system constant in terms of components and performance. Fig. 11 shows the variation in system LCOE when the inverter cost is varied. The results presented in Fig. 11 can be used as baseline for system LCOE, when developing a similarly rated SiC-based PV inverter. Multiple such cases can be developed by varying the inverter life, efficiency, etc., to create a baseline that will be useful for PV inverter developers.

It should be noted that all the discussions regarding the SiC inverter LCOE to this point have been based on the system using thin-film PV modules. This is done because thin-film PV modules have a lower thermal coefficient of drift as compared to Si PV modules. This is important in the context of the developed SiC inverter because it does not include the dc-dc stage to compensate for the voltage drift as the temperature starts increasing. Fig. 12 shows the result of a system with silicon modules instead of thin film. The result is ~2,000-kWh per year of power loss. The lifetime cost is $0.01/kwh higher.



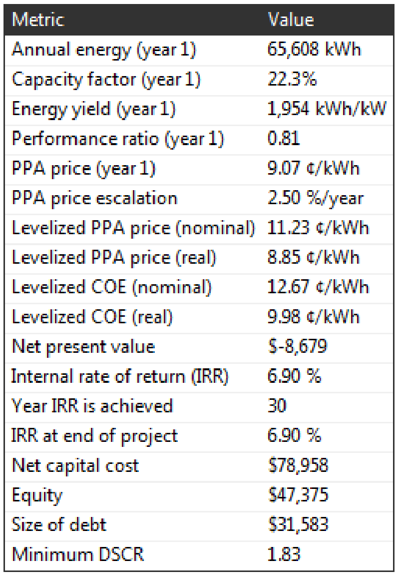
Metric	Value
Annual energy (year 1)	98,721 kWh
Capacity factor (year 1)	22.1%
Energy yield (year 1)	1,932 kWh/kW
Performance ratio (year 1)	0.81
PPA price (year 1)	8.96 ¢/kWh
PPA price escalation	2.50 %/year
Levelized PPA price (nominal)	11.10 ¢/kWh
Levelized PPA price (real)	8.74 ¢/kWh
Levelized COE (nominal)	12.47 ¢/kWh
Levelized COE (real)	9.83 ¢/kWh
Net present value	$-12,492
Internal rate of return (IRR)	6.90 %
Year IRR is achieved	30
IRR at end of project	6.90 %
Net capital cost	$117,464
Equity	$70,478
Size of debt	$46,986
Minimum DSCR	1.86

Fig. 10. Details of the LCOE of a PV system installed in Phoenix, AZ, formed using Gamma inverter, thin-film PV modules and assuming future die pricing.



Metric	Value
Annual energy (year 1)	96,126 kWh
Capacity factor (year 1)	21.5%
Energy yield (year 1)	1,885 kWh/kW
Performance ratio (year 1)	0.79
PPA price (year 1)	9.21 ¢/kWh
PPA price escalation	2.50 %/year
Levelized PPA price (nominal)	11.40 ¢/kWh
Levelized PPA price (real)	8.98 ¢/kWh
Levelized COE (nominal)	12.81 ¢/kWh
Levelized COE (real)	10.10 ¢/kWh
Net present value	$-12,472
Internal rate of return (IRR)	6.90 %
Year IRR is achieved	30
IRR at end of project	6.90 %
Net capital cost	$117,223
Equity	$70,334
Size of debt	$46,889
Minimum DSCR	1.87

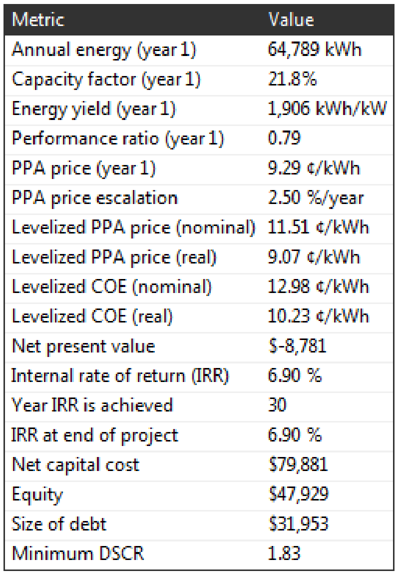
Fig. 12. Details of the LCOE of a PV system installed in Phoenix, AZ, formed using Gamma inverter, Si PV modules and assuming future die pricing.



Metric	Value
Annual energy (year 1)	65,608 kWh
Capacity factor (year 1)	22.3%
Energy yield (year 1)	1,954 kWh/kW
Performance ratio (year 1)	0.81
PPA price (year 1)	9.07 ¢/kWh
PPA price escalation	2.50 %/year
Levelized PPA price (nominal)	11.23 ¢/kWh
Levelized PPA price (real)	8.85 ¢/kWh
Levelized COE (nominal)	12.67 ¢/kWh
Levelized COE (real)	9.98 ¢/kWh
Net present value	$-8,679
Internal rate of return (IRR)	6.90 %
Year IRR is achieved	30
IRR at end of project	6.90 %
Net capital cost	$78,958
Equity	$47,375
Size of debt	$31,583
Minimum DSCR	1.83

Fig. 14. Details of the LCOE of a PV system installed in Phoenix, AZ, formed using Si based commercial PV inverter and thin film PV modules.

The next two analyses are for PV systems formed using a commercially available, Si devices-based, state-of-the-art PV inverter. The inverter has ratings that are similar to the developed Gamma inverter and does not include a dc-dc converter stage. Fig. 14 and Fig. 13 present the LCOE details when using the commercially, available state-of-the-art, Si-based PV inverter in the PV system with thin-film PV modules and Si PV modules, respectively. It can be observed from these results the LCOE for a PV system formed using a state-of-the-art Si PV inverter is higher than that of the corresponding LCOE for the Gamma inverter-based PV system. It should be noted that the life of the SiC inverter will be longer than that of Si based inverter since it is formed using film capacitors instead of the electrolytic capacitors used in the Si inverter; however, for the analysis, this is not considered. If the lifetime impact of the electrolytic capacitors were also used, then the LCOE of the Gamma inverter would be even lower. Additionally, the substantial size differential realized with a SiC inverter compared to a Si inverter is not quantified and studied here.



Metric	Value
Annual energy (year 1)	64,789 kWh
Capacity factor (year 1)	21.8%
Energy yield (year 1)	1,906 kWh/kW
Performance ratio (year 1)	0.79
PPA price (year 1)	9.29 ¢/kWh
PPA price escalation	2.50 %/year
Levelized PPA price (nominal)	11.51 ¢/kWh
Levelized PPA price (real)	9.07 ¢/kWh
Levelized COE (nominal)	12.98 ¢/kWh
Levelized COE (real)	10.23 ¢/kWh
Net present value	$-8,781
Internal rate of return (IRR)	6.90 %
Year IRR is achieved	30
IRR at end of project	6.90 %
Net capital cost	$79,881
Equity	$47,929
Size of debt	$31,953
Minimum DSCR	1.83

Fig. 13. Details of the LCOE of a PV system installed in Phoenix, AZ, formed using Si based commercial PV inverter and Si PV modules.

V. CONCLUSION

In this paper, a bottoms-up cost model of a SiC-based PV inverter has been presented. The MSP for a SiC PV inverter formed using off-the-shelf components has been presented in this paper. The MSP comparison between inverters when using electrolytic capacitors at the dc-bus and when using film capacitors at the dc-bus has also been presented in this paper. The inverter performance and the LCOE of a PV system using the developed inverter has been quantified. It has been shown that even with increased inverter cost, the LCOE of a PV system using SiC-based inverter is reduced. It has been shown that through the performance capabilities and volume costs for the Gamma inverter, there is the potential for this to be on par economically with the current benchmark systems when looking at the LCOE. Increases in lifetime, efficiency, and further cost reductions will only make the system more attractive. In this paper, a comparison of LCOE for PV systems formed using a SiC PV inverter and Si state-of-the-inverter has also been presented. It has been shown that the LCOE for the SiC-based inverter based PV system is less than that of a PV system with Si-based system.

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REFERENCES

[1] K. Horowitz, T. Remo, and S. Reese, “A Manufacturing Cost and Supply Chain Analysis of SiC Power Electronics Applicable to Medium-Voltage Motor Drives,” No. NREL/TP--6A20-67694. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017.

[2] D.M. Powell, Mark Winkler, Choi H, Tonio Buonassisi. "Crystalline silicon photovoltaics: A cost analysis framework for determining technology pathways to reach baseload electricity costs," Energy and Environmental Science, vol. 5, pp. 5874-5883, 2012.

[3] Shiao, M., and S. Moskowitz. "The global PV inverter landscape 2013: Technologies, Markets and Survivors." (2015).

[4] H. Wang, M. Liserre, and F. Blaabjerg, “Toward reliable power electronics: Challenges, design tools, and opportunities,” *IEEE Ind. Electron. Mag*., vol. 7, no. 2, pp. 17–26, Jun. 2013.

[5] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, “An industry-based survey of reliability in power electronic converters,” IEEE Trans. Ind. Appl., vol. 47, no. 3, pp. 1441–1451, May 2011.

[6] R. Fu, D. Feldman, R. Margolis, M. Woodhouse, and K. Ardani “US solar photovoltaic system cost benchmark: Q1 2017,” No. NREL/TP-6A20-68925. National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2017.

[7] System Advisor Model Version 2017.9.5 (SAM 2017.9.5). National Renewable Energy Laboratory. Golden, CO. https://sam.nrel.gov/content/downloads.