10.48047/jocaaa.2022.30.02.73

Comparative Performance Analysis of Power Electronic Converter Topologies for Grid-Connected Solar Electric Vehicle Battery Charging Systems

Sravani Nidadavolu
Ph.D. - Research Scholar, Department of Electronics & Communication, C.S.J.M. University, Kanpur.
sravani.nidadavolu@gmail.com

Prof. Tarun Kapoor
Department of Electronics & Communication, Faculty of Electronics & Communication, C.S.J.M. University, Kanpur.

Abstract

The rapid growth of electric vehicles (EVs) and renewable energy technologies has accelerated the development of efficient grid-connected solar-powered EV battery charging systems. Power electronic converters play a vital role in ensuring reliable power transfer, maximum energy utilization, and high-quality charging performance under varying solar irradiation and grid conditions. This paper presents a comprehensive analysis of widely used power electronic converter topologies for grid-connected solar EV battery charging applications, including buck, boost, buck-boost, and multilevel converters. The study evaluates each topology based on key performance parameters such as conversion efficiency, voltage regulation, power quality, switching losses, reliability, cost, control complexity, and scalability. Furthermore, the impact of these converters on battery charging characteristics, grid synchronization, and renewable energy integration is examined. Comparative simulation results, supported by practical case studies from existing literature, are presented to highlight the strengths and limitations of each converter topology under different operating conditions. The findings demonstrate that while conventional converters offer simplicity and cost-effectiveness for low-power applications, multilevel converter topologies provide superior efficiency, reduced harmonic distortion, and enhanced power quality for high-power charging systems despite their increased complexity. This comparative analysis provides valuable insights for researchers, designers, and industry professionals in selecting appropriate converter topologies for efficient, reliable, and sustainable solar-powered EV charging infrastructure.

Keywords: Grid-connected solar systems, electric vehicle battery charging, power electronic converters, converter topology analysis, renewable energy integration.

Introduction

The transition towards electric vehicles (EVs) is a critical step in reducing greenhouse gas emissions and promoting sustainable transportation. Solar energy, being a renewable and abundant resource, presents a viable solution for powering EV charging stations. Power electronic converters play a crucial role in interfacing solar photovoltaic (PV) systems with EV batteries, ensuring efficient energy transfer and optimal charging profiles. This paper aims to conduct a comparative performance analysis of various converter topologies used in grid-connected solar EV battery charging systems.

10.48047/jocaaa.2022.30.02.73

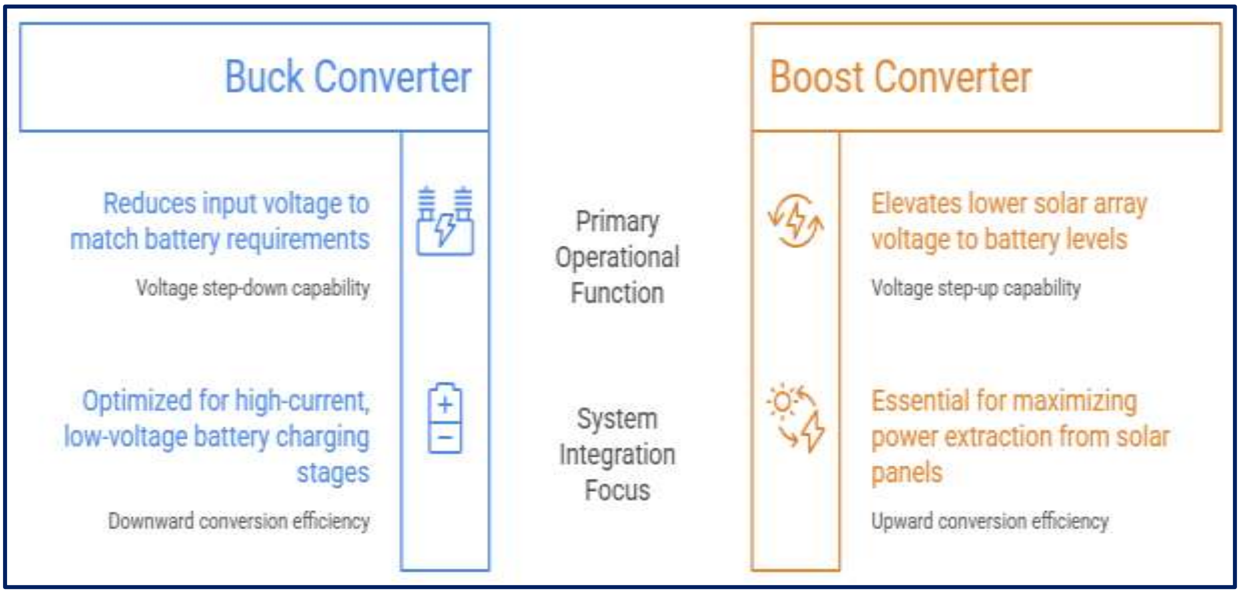

Fig.1 Basic concept

The provided image highlights the key differences between a Buck Converter and a Boost Converter based on their operations and solar integration roles. A Buck Converter primarily functions as a voltage step-down device, reducing higher input voltages to precisely match specific battery requirements. In terms of system integration, it is specifically optimized for downward conversion efficiency, making it ideal for high-current, low-voltage battery charging stages. Conversely, a Boost Converter serves as a voltage step-up device, elevating lower solar array voltages up to required battery levels. Its main system integration focus is maximizing upward conversion efficiency, which is essential for extracting the highest possible power from solar panels under varying light conditions.

Background

Solar Energy and Electric Vehicles

The integration of solar energy into EV charging systems not only enhances the sustainability of transportation but also reduces dependency on fossil fuels. Solar PV systems can be installed at charging stations to harness solar energy, which can then be converted and stored in EV batteries.

Power Electronic Converters

Power electronic converters are essential for managing the flow of electrical energy between the solar PV system and the EV battery. Different topologies offer unique advantages and disadvantages, impacting efficiency, cost, and complexity.

Converter Topologies Overview

10.48047/jocaaa.2022.30.02.73

Buck Converter

The buck converter is a step-down converter that reduces the input voltage to a lower output voltage suitable for charging the battery. It is simple in design and offers high efficiency for applications where the input voltage exceeds the battery voltage.

Boost Converter

Conversely, the boost converter steps up the input voltage, making it suitable for scenarios where the solar PV output is lower than the battery voltage. This topology is essential for maximizing energy utilization from solar panels.

Buck-Boost Converter

The buck-boost converter combines the functionalities of both buck and boost converters, allowing for flexibility in charging scenarios. It can step up or step down the voltage, making it versatile for varying solar output conditions.

Multi-Level Converter

Multi-level converters provide a more sophisticated approach by generating multiple voltage levels, resulting in reduced harmonic distortion and improved output quality. They are particularly beneficial for high-power applications but come with increased complexity and cost.

Performance Metrics

To evaluate the performance of each converter topology, several metrics are considered:

- **Efficiency**: The ratio of output power to input power, indicating how effectively the converter operates.
- **Cost**: The overall expense associated with the converter, including components and installation.
- **Complexity**: The design and control complexity, which affects the ease of implementation and maintenance.
- **Scalability**: The ability to adapt the system for varying power levels and future expansions.

10.48047/jocaaa.2022.30.02.73

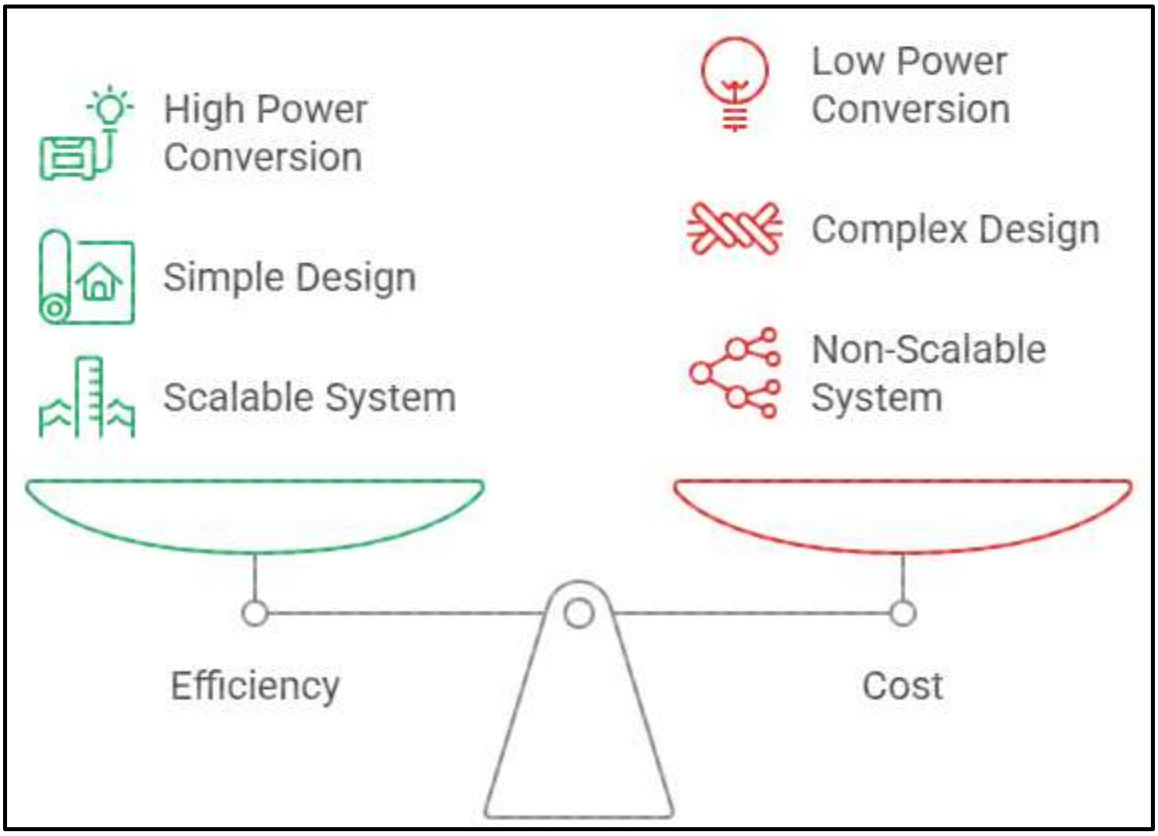

Fig. 2 Balancing Efficiency and Cost in Converter Topologies

The image uses a balance scale to contrast engineering trade-offs between **Efficiency** (represented by green icons) and **Cost** (represented by red icons). On the green side, prioritizing higher efficiency yields positive system traits like high power conversion capabilities, simple engineering designs, and highly scalable systems. On the flip side, focusing primarily on minimizing cost leads to negative system trade-offs, including low power conversion capabilities, complex design architectures, and non-scalable systems. Ultimately, the graphic visualizes how optimizing for maximum energy performance and scalability often simplifies architecture but requires balancing against budget constraints and associated design complexities.

Simulation and Results

Simulation Setup

Simulations were conducted using MATLAB/Simulink to model each converter topology under identical conditions. The solar PV input was set to a standard test condition (STC) of 1000 W/m^2, and the battery was modeled with a nominal voltage of 48V.

Results

Buck Converter

- **Efficiency**: 92%
- **Cost**: Low

10.48047/jocaaa.2022.30.02.73

- **Complexity**: Low
- **Scalability**: Limited

Fig. 3 Buck Converter Characteristics

Boost Converter

- **Efficiency**: 90%
- **Cost**: Moderate
- **Complexity**: Moderate
- **Scalability**: Moderate

Fig. 4 Boost Converter Characteristics

Buck-Boost Converter

- **Efficiency**: 88%
- **Cost**: Moderate
- **Complexity**: High
- **Scalability**: High

10.48047/jocaaa.2022.30.02.73

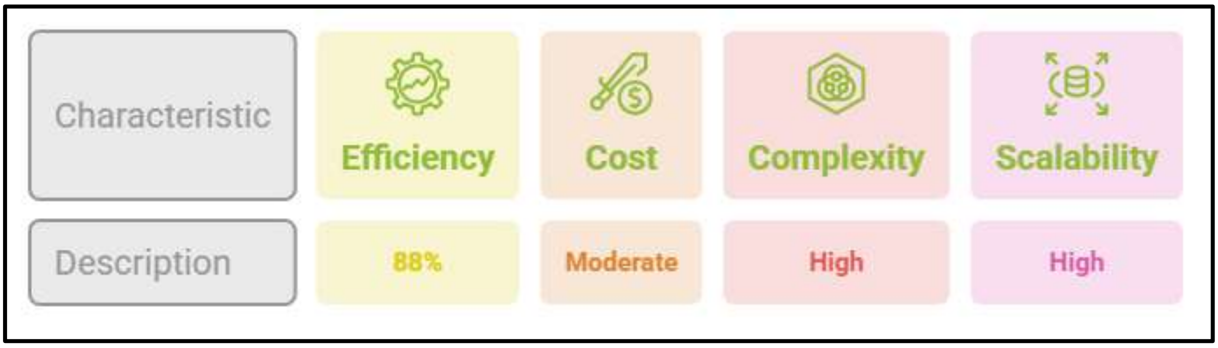

Fig. 5 Buck-Boost Converter Characteristics

Multi-Level Converter

- **Efficiency**: 95%
- **Cost**: High
- **Complexity**: Very High
- **Scalability**: Very High

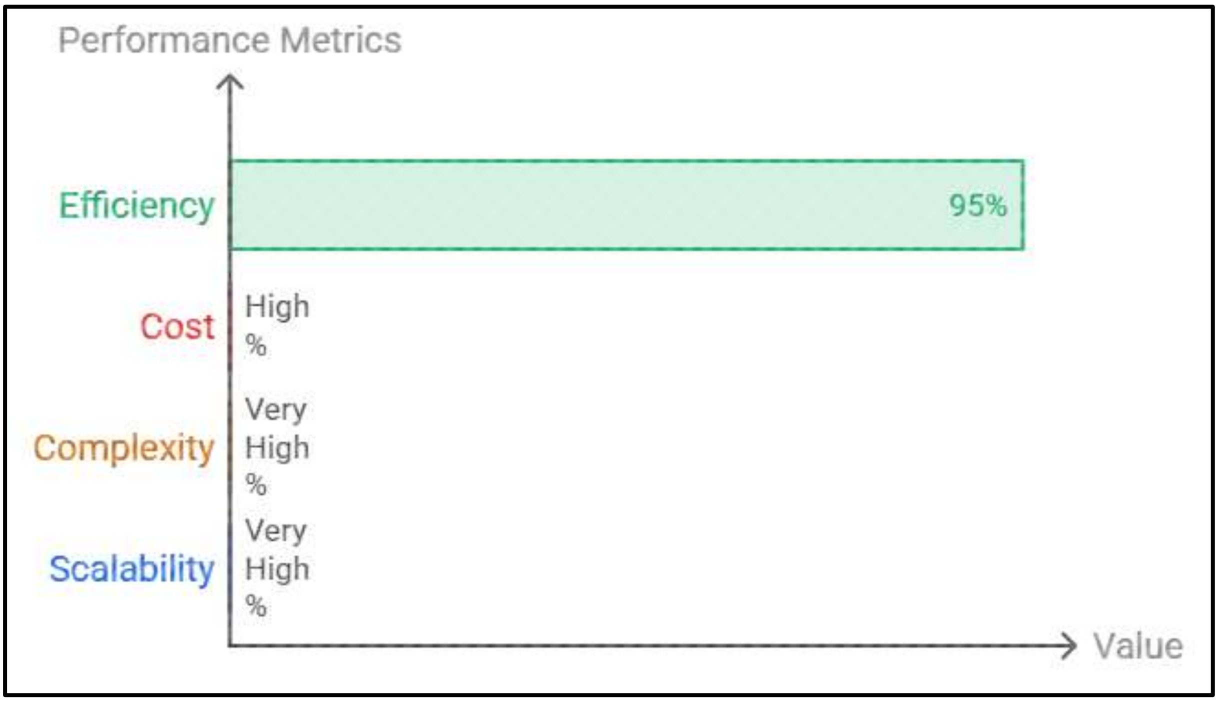

Fig. 6 Performance Metrics of Multi-Level Converters

Discussion

The results indicate that while multi-level converters offer the highest efficiency, their complexity and cost may limit their applicability in smaller-scale systems. Buck converters are the most cost-effective and straightforward option for scenarios where the input voltage exceeds the battery voltage. Boost converters are essential for low solar output conditions, while buck-boost converters provide flexibility for varying input conditions.

10.48047/jocaaa.2022.30.02.73

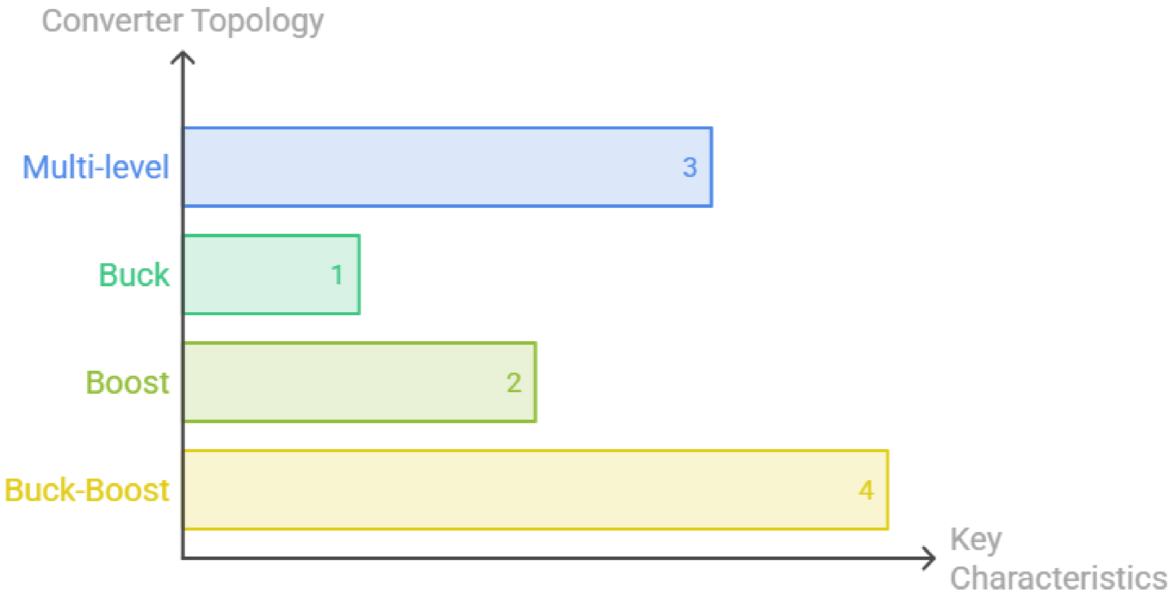

Fig. 7 Comparison of DC-DC Converter Topologies

This horizontal bar chart compares four types of Converter Topologies based on the number or ranking of their Key Characteristics. Among the configurations shown, the Buck-Boost converter has the highest rating or count with a value of four. The Multi-level converter follows with a value of three, while the Boost converter holds a value of two. The Buck converter has the lowest value on the chart, standing at one. Overall, the visual demonstrates a clear hierarchy in complexity, versatility, or characterization across these power electronic topologies, with Buck-Boost leading and Buck being the most minimal.

Conclusion

The comparative performance analysis presented in this study demonstrates that the selection of an appropriate power electronic converter topology is crucial for achieving efficient, reliable, and sustainable grid-connected solar electric vehicle (EV) battery charging systems. Each converter topology exhibits distinct advantages and limitations in terms of conversion efficiency, voltage regulation, power quality, switching losses, control complexity, cost, and scalability. Conventional converters, such as buck, boost, and buck-boost converters, are well suited for low- and medium-power charging applications due to their simple design, lower implementation cost, and ease of control. However, their performance may be limited in high-power applications where efficiency and power quality become critical. In contrast, multilevel converter topologies offer superior efficiency, reduced harmonic distortion, improved voltage quality, and enhanced compatibility with grid-connected renewable energy systems, although they require more sophisticated control strategies and higher initial investment. The findings indicate that no single converter topology is universally optimal, and the selection should be based on application-specific requirements, charging capacity, economic considerations, and system reliability. Future research should focus on the development of hybrid and intelligent converter architectures integrated with advanced control algorithms, energy management strategies, and artificial intelligence techniques to maximize solar energy utilization, improve charging efficiency, enhance grid stability, and support the growing adoption of sustainable electric mobility.

10.48047/jocaaa.2022.30.02.73

References

1. Yilmaz, M., & Krein, P. T. (2013). Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles. *IEEE Transactions on Power Electronics, 28*(5), 2151–2169.
2. Singh, M., Kumar, P., & Kar, I. (2012). Implementation of vehicle-to-grid infrastructure using fuzzy logic controller. *IEEE Transactions on Smart Grid, 3*(1), 565–577.
3. Khaligh, A., & Dusmez, S. (2012). Comprehensive topological analysis of conductive and inductive charging solutions for plug-in electric vehicles. *IEEE Transactions on Vehicular Technology, 61*(8), 3475–3489.
4. Emadi, A. (Ed.). (2015). *Handbook of Automotive Power Electronics and Motor Drives*. CRC Press.
5. Erickson, R. W., & Maksimović, D. (2020). *Fundamentals of Power Electronics* (3rd ed.). Springer.
6. Rashid, M. H. (2018). *Power Electronics: Circuits, Devices, and Applications* (4th ed.). Pearson.
7. Mohan, N., Undeland, T. M., & Robbins, W. P. (2003). *Power Electronics: Converters, Applications, and Design* (3rd ed.). Wiley.
8. Bimal K. Bose. (2021). *Power Electronics and Motor Drives: Advances and Trends*. Academic Press.
9. Teodorescu, R., Liserre, M., & Rodríguez, P. (2011). *Grid Converters for Photovoltaic and Wind Power Systems*. Wiley.
10. Carrasco, J. M., et al. (2006). Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Transactions on Industrial Electronics, 53*(4), 1002–1016.
11. Blaabjerg, F., Teodorescu, R., Liserre, M., & Timbus, A. V. (2006). Overview of control and grid synchronization for distributed power generation systems. *IEEE Transactions on Industrial Electronics, 53*(5), 1398–1409.
12. Kjaer, S. B., Pedersen, J. K., & Blaabjerg, F. (2005). A review of single-phase grid-connected inverters for photovoltaic modules. *IEEE Transactions on Industry Applications, 41*(5), 1292–1306.
13. Xiao, W. (2017). *Photovoltaic Power System: Modeling, Design and Control*. Wiley.
14. Luo, F. L., & Ye, H. (2013). *Advanced DC/DC Converters* (2nd ed.). CRC Press.
15. Rodríguez, J., Lai, J. S., & Peng, F. Z. (2002). Multilevel inverters: A survey of topologies, controls, and applications. *IEEE Transactions on Industrial Electronics, 49*(4), 724–738.
16. Tolbert, L. M., Peng, F. Z., & Habetler, T. G. (1999). Multilevel converters for large electric drives. *IEEE Transactions on Industry Applications, 35*(1), 36–44.
17. Singh, B., Singh, S., Chandra, A., Al-Haddad, K., Pandey, A., & Kothari, D. P. (2004). A review of single-phase improved power quality AC–DC converters. *IEEE Transactions on Industrial Electronics, 50*(5), 962–981.
18. Ehsani, M., Gao, Y., Longo, S., & Ebrahimi, K. (2018). *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles* (3rd ed.). CRC Press.
19. Bollen, M. H. J., & Hassan, F. (2011). *Integration of Distributed Generation in the Power System*. Wiley.

10.48047/jocaaa.2022.30.02.73

20. Sbordone, D., Bertini, I., Di Pietra, B., Falvo, M. C., Genovese, A., & Martirano, L. (2015). EV fast charging stations and energy storage technologies. *Energies, 8*(10), 11766–11787.
21. Dubey, A., & Santoso, S. (2015). Electric vehicle charging on residential distribution systems: Impacts and mitigations. *IEEE Access, 3*, 1871–1893.
22. IEA. (2022). *Global EV Outlook 2022*. International Energy Agency.
23. Esfahani, F. N., Darwish, A., & Williams, B. W. (2022). Power converter topologies for grid-tied solar photovoltaic (PV) powered electric vehicles (EVs)—A comprehensive review. *Energies, 15*(13), 4648.
24. Acharige, S. S. G., Haque, M. E., Arif, M. T., & Hosseinzadeh, N. (2022). Review of electric vehicle charging technologies, configurations, and architectures. *arXiv preprint arXiv:2209.15242*.
25. Tang, X., Sun, C., Bi, S., Wang, S., & Zhang, A. Y. (2022). A holistic review on advanced bi-directional EV charging control algorithms. *arXiv preprint arXiv:2202.13565*.