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Environmental Aspect of Using a High Step-Up No Isolated DC-DC Converter for Solar Photovoltaic Applications: Life Cycle Assessment Point of View

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ABSTRACT

This study undertakes a comprehensive investigation into the environmental implications of adopting a High Step-Up Non-Isolated (HSUNI) DC-DC Converter in solar photovoltaic (PV) applications using a life cycle assessment (LCA) approach. The LCA methodology is applied to thoroughly evaluate the environmental footprint of the converter, considering its entire life cycle, from raw material extraction and manufacturing to operation and end-of-life disposal. Vital environmental indicators such as greenhouse gas emissions, energy consumption, and resource depletion are assessed to quantify the converter's environmental impact. The study also explores potential variations in environmental performance based on different manufacturing processes, materials, and usage scenarios. The results show that, compared to the control, all scenarios reduced the midpoint impacts by about 5 to 80%. A sensitivity analysis indicates that usage scenarios, followed by manufacturing processes, have the highest sensitivity score on endpoint impacts, about 20 to 25% higher than other factors. The findings of this study significantly contribute to the broader discourse on sustainable energy technologies, providing valuable insights for stakeholders in the renewable energy sector.

1. Introduction

The DC-DC converter, a crucial electronic component, is at the heart of the functionality and efficiency of solar PV installations. It is designed to optimize the conversion and transfer of power between PV modules and the electrical grid or load. As the solar energy landscape evolves, these

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converters' performance, reliability, and adaptability play a pivotal role in ensuring the seamless integration and maximized utilization of solar power [1, 2].

Given the historical limitations of traditional DC-DC converter technologies regarding efficiency, scalability, and adaptability to diverse environmental conditions, there is a clear need for innovation. Recent developments in converter design, such as High Step-Up and Non-Isolated topologies, have emerged as promising solutions to address these limitations [3, 4]. This study aims to explore these advancements, challenges, and implications.

This investigation is a testament to our commitment to providing a comprehensive understanding of the evolving landscape of DC-DC converters in the context of solar PV systems. By delving into the intricacies of emerging technologies and comparing various converter topologies, we seek to elucidate the potential benefits and trade-offs associated with their implementation. Our findings not only shed light on the challenges but also highlight the potential for more efficient and sustainable solar PV systems. Moreover, the study extends its focus beyond technical considerations to encompass economic and environmental dimensions, evaluating the cost-effectiveness and sustainability of advanced DC-DC converters throughout their life cycle in a comprehensive manner.

As the transition to renewable energy sources accelerates, unraveling the complexities of DC-DC converter technology becomes paramount for engineers, researchers, and policymakers alike. This exploration contributes to the ongoing discourse on optimizing solar energy conversion and offers insights that can shape the future trajectory of clean and sustainable energy solutions. This study contributes to the evolution of efficient and environmentally conscious solar energy systems by examining DC-DC converters tailored for solar PV applications.

The significance of the High Step-Up Non-Isolated (HSUNI) DC-DC Converter lies in its pivotal role in enhancing the efficiency and performance of solar PV systems. Traditional DC-DC converters are often constrained by limitations in their step-up capabilities, hindering their ability to efficiently boost the low voltage generated by PV modules to levels suitable for grid integration or effective power delivery. The HSUNI DC-DC Converter addresses this limitation by providing a substantially increased voltage conversion ratio, enabling more effective energy harvesting from low-voltage PV sources. This innovation is particularly crucial when solar installations experience varying sunlight conditions or partial shading, as the converter ensures optimal power extraction even in suboptimal environments. By mitigating voltage losses and improving overall energy yield, the HSUNI DC-DC Converter significantly contributes to solar PV systems' economic viability and reliability, advancing the widespread adoption of clean and sustainable energy solutions.

The importance of the HSUNI DC-DC Converter extends beyond immediate performance gains to encompass broader environmental considerations. The converter's ability to enhance energy conversion efficiency directly translates into reduced greenhouse gas emissions and a smaller ecological footprint over the entire life cycle of a solar PV system. As the world seeks to transition towards a more sustainable energy paradigm, technologies that maximize energy output while minimizing environmental impact become increasingly crucial. The HSUNI DC-DC Converter aligns with these objectives by optimizing the utilization of solar energy resources, contributing to reducing carbon emissions, and bolstering the overall sustainability of solar PV applications.

Conducting an environmental analysis using a life cycle assessment (LCA) for an HSUNI DC-DC Converter in solar PV applications is imperative to comprehensively evaluate and understand the ecological impact of this technology throughout its entire lifecycle. Firstly, the extraction and processing of raw materials, along with the manufacturing phase, contribute significantly to the environmental footprint of any electronic component. By employing an LCA, we can quantify the energy consumption, emissions, and resource depletion associated with these initial stages, providing insights into the environmental cost of producing the HSUNI DC-DC Converter. This holistic view helps identify opportunities for eco-friendly material selection, manufacturing process optimization, and sustainable sourcing practices, ultimately minimizing the environmental burden of the converter from its inception.

The operational phase of the HSUNI DC-DC Converter plays a critical role in the overall environmental analysis. Understanding the energy efficiency and performance characteristics during its use in solar PV systems allows for a nuanced assessment of the technology's impact on resource conservation and emissions reduction. The LCA facilitates the comparison of different operational scenarios, helping identify optimal usage patterns and potential areas for efficiency improvements. This phase is particularly significant as it directly influences the converter's contribution to the overall sustainability of solar PV applications and guides the development of strategies to enhance its operational eco-efficiency.

An LCA provides insights into the end-of-life considerations for the HSUNI DC-DC Converter. Examining disposal methods, recyclability, and environmental impacts associated with the converter's decommissioning is crucial for establishing responsible waste management practices. By identifying opportunities for recycling or safe disposal, the study contributes to the development of circular economy principles within the electronics industry, ensuring that the environmental consequences of the converter's end-of-life phase are mitigated. An ecological analysis using LCA for the HSUNI DC-DC Converter is essential for promoting sustainable practices throughout its entire lifecycle, from production and operation to decommissioning.

Several studies have been presented on developing and applying DC-DC converters in PV systems. But boldly and cautiously, no similar case was observed from the point of view of the environmental effects of using these converters in PV systems.

The study conducted by Cao et al. [5] introduced various distributed PV architectures and DC-DC converters featuring maximum power point tracking (MPPT). The investigation explored the concept of partial power processing, a strategy aimed at reducing losses and enhancing efficiency by allowing only a fraction of the power to undergo processing through the DC-DC converter. The thesis proposed a novel partial power-isolated DC-DC converter with MPPT capabilities. This converter employed a controller that selectively engages the buck, boost portions, or both in response to the MPPT input signal. This dynamic adjustment aimed to achieve the desired output voltage and maximum power. The proposed topology involved series-connected DC-DC converters, each carrying an equal string current and adjusting its output voltage proportionally to the available power of the connected PV module. This configuration allowed individual PV modules to operate at maximum power points, accommodating varying or mismatched solar irradiance conditions while maintaining a constant total DC string voltage. The functionality of the proposed circuit was validated through simulation using PLECS software.

The study by Saravanan et al. [6] introduced a non-isolated high-voltage gain DC-DC converter. The boost, Single-Ended Primary Inductor Converter (SEPIC), and modified SEPIC converters are scrutinized, and their performances are contrasted with the newly proposed converter. Specifically designed for an input voltage of 15 V and an output voltage of 150 V with 100 W output power, the proposed converter achieves an efficiency of 92.5%. This efficiency surpassed that of the other analyzed converter models. Furthermore, the proposed converter exhibited reduced input current and low switching voltage stress.

The study by Tangavelo et al. [7] introduced a novel topology for an HSUNI DC-DC converter designed for solar PV applications. The proposed converter exhibited several advantages, including low-voltage stress on the switches, high gain with a low duty ratio, and the maintenance of a continuous input current. The study provided analytical waveforms for the proposed converter in both continuous and discontinuous modes of operation and an analysis of voltage stress. The voltage gain and efficiency of the converter in the presence of parasitic elements were derived, and a performance comparison was made with recently reported high-gain converter topologies.

The study by Maheswari et al. [8] introduced an isolated single-switch high step-up DC/DC converter designed for solar PV applications. The proposed converter comprised a single switch, two voltage doubler circuits, and a three-winding transformer. To achieve a high step-up voltage gain, the four capacitors in the voltage doubler circuits were charged in parallel and discharged in series by the secondary and tertiary winding of the three-winding transformer. This configuration enhanced the voltage gain and effectively mitigated voltage stress on the switch by absorbing energy in parallel, which was particularly beneficial for switches with low turns ratio and low duty cycle.

The study by Ramu et al. [9] presented a novel energy management strategy (EMS) that leverages an Artificial Neural Network (ANN) to control a DC microgrid equipped with a hybrid energy storage system (HESS). The HESS was interfaced with the DC microgrid using a bidirectional converter (BC), facilitating energy exchange between the HESS's battery and supercapacitor (SC) components.

To enhance the power generation of the photovoltaic (PV) network, the study by Samiulla et al. [10] proposed a modified sliding-mode maximum power point tracking (MPPT) controller. This MPPT controller was interfaced with the solar insolation system to capture more sunlight, thereby shifting the operation of the solar system from a local MPP to the required global MPP.

Satyanarayana et al. [11] presented a power management and control strategy for a standalone photovoltaic (PV) and battery-integrated hybrid system, utilizing a high-gain DC-DC converter suitable for DC microgrid applications. The necessity of the high-gain DC-DC converter arose from the typically low output voltage generated by PV systems.

Rajamani et al. [12] presented a dual-output DC-DC power conversion system that leverages photovoltaic (PV) technology. The proposed system architecture connects the PV system to a series-compensated buck-boost converter to harvest solar energy.

The study by Mizani et al. [13] presented a novel high-step-up DC-DC converter architecture that does not require any coupled inductors or transformers. The proposed converter structure combines two boost techniques - switched inductor and switched capacitor - and employs them concurrently. The switched inductor technique provided an initial voltage boosting stage, while the switched capacitor stage further increased the voltage conversion ratio. The converter could achieve a high step-up capability by synergistically integrating these two boost mechanisms without needing coupled magnetic components, such as inductors or transformers.

According to the study conducted by Imperiali et al. [14], investigating environmental effects was one of the key but needed aspects of analyzing the impact of converters in PV systems. However, Imperiali et al. [14] conducted an environmental assessment of AC-DC converters in PV systems and proposed evaluating the ecological effects of DC-DC converters in future works. Table 1 also summarises the studies conducted in the field.

Table 1. The conducted studies in the field

Reference	Type of converter	Module type	Environmental assessment
[15]	DC-DC	Cascaded	☒
[16]	DC-DC	Boosting	☒
[17]	DC-DC	high-gain	☒
[18]	DC-DC	Boosting	☒
[19]	DC-DC	Module Integrated	☒
[20]	DC-DC	Boosting	☒
[21]	DC-DC	high-gain	☑
[22]	DC-DC	Full bridge	☒
[14]	AC-DC	high-gain	☑
The present study	DC-DC	High Step-Up: No isolated	☑

As Table 1 indicates, no study has been conducted to evaluate the environmental impacts of high step-up non-isolated (HSUNI) DC-DC Converters in solar photovoltaic (PV) applications. The present study was developed to address this research gap.

The study's main novelty lies in its comprehensive life cycle assessment of a high step-up, non-isolated DC-DC converter specifically designed for solar photovoltaic applications, evaluating its environmental impact across its entire lifespan. This study was integrated into three parts: system design presentation, LCA development, and results presentation.

2. Materials and Methods

2.1. DC-DC converter

The circuit topology of the proposed non-isolated SS-DDC is depicted in Fig. 1. This configuration includes an active semiconductor switch (Q), four diodes (D1, D2, D3, D4), three passive capacitors (C1, C2, C3), two passive inductors (L1, L2), an output diode (D0), and an output capacitor (C0). The modified switched inductor cell (MSIC) incorporates L1, L2, D1, D2, and C1. As shown in Fig. 1, the MSIC topology is arranged with the boost capacitor (C1) in place of the diode in SIC, aiming to decrease the voltage stress on semiconductor devices and elevate the output voltage level.

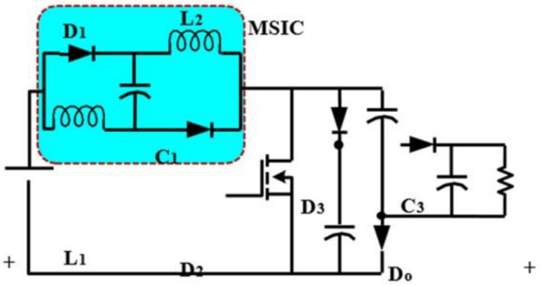


Figure 1. Proposed non-isolated step-up DC-DC converter with MSIC

2.2. Life cycle assessment (LCA)

The LCA technique is a skilled method for assessing the supplies, mechanisms, and facilities employed throughout the production process, from raw material sourcing, formation, and steps to respective production frameworks and the possible future environmental impacts of such operations [23]. LCA begins with a technique of dividing how distinct products influence the environment. LCA is a standardized method for supplying companies and governments with a solid scientific foundation for environmental sustainability [24]. LCA examines the ecological impacts of composite materials in terms of their reusable nature [25]. Cradle-to-grave analysis (LCA) investigates a product's or service's environmental impact from conception to disposal, covering all stages of manufacturing, shipping, end-user consumption, and waste disposal [26, 27]. The four stages of life cycle analysis (LCA) are defined: defining objectives and scope, conducting an inventory check, implementing an impact assessment, and evaluating the results. Figure 2 depicts a simplified diagram of the stages in an LCA.

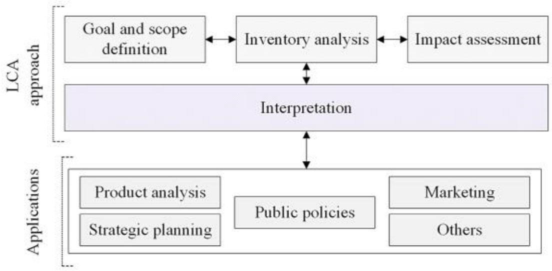


Figure 2. Steps of the LCA approach

The scope of the LCA approach covers system boundaries and the quantity of information that varies depending on the topic and the research's application domain. The strength and area of a customized LCA can vary greatly depending on its purpose. The system in this study involves improving the power generation from PV systems using DC-DC converters. The current LCA aims to thoroughly examine the environmental effects of using the proposed DC-DC converters in PV systems.

The functional unit (FU) measures allusion for inventory data in LCA [28]. FU is frequently referred to in terms of system output [29]. This investigation establishes the optimum FU for each treatment as 1 kW of power generation. Moreover, different subsystems are investigated separately from the preceding steps to appreciate the environmental implications of each step. Indeed, from the standpoint of ecological effects, this form of calculation in LCA could provide extra insight into the functional character of each stage.

The quantification of the boundaries' outputs and inputs is defined as LCI. This stage is divided into four concurrent sub-stages. All processes associated with the product life cycle should be recognized during the first phase. Extracting raw materials and energy from the environment is the starting point for all activities. The gathering of data relevant to each procedure is required in the second stage. This is the most demanding phase of the LCA. Research findings, LCA professional literature, and company and government records can all be used to gather data. The third stage involves re-explaining system boundaries to acquire an essential matrix of platform boundaries and eliminate operations that cross system boundaries. FU eventually regulates all process inputs and outputs [20]. In essence, the LCA evaluation is divided into two parts: indirect and direct emissions.

Direct emissions are those emitted by sources controlled by the reporting entity. This study links direct emissions to biogas production. Indirect emissions are those caused by the reported object's actions but originate at facilities controlled or owned by third parties. Furthermore, these emissions are linked to the production of several chemicals in various components of energy generation systems—the amount of each input needed for these emissions. Table 2 shows the LCI developed for this study.

Table 2. LCI of power generation of the DC-DC converter

Material	Amount per converter (g)	CO2 intensity (kg CO2/kg)
fiber reinforced	0.00023	0.0081
Gold	0.0000004	0.3
Nylon	0.00015	0.0065
Copper	0.00021	0.0035
Polycarbonate	0.000034	0.006
Brass	0.00004	0.00439
Tin	0.000005	0.00018
Zirconium	0.0000076	0.00097
Encapsulation	0.0000104	0.00055
Hardener	0.000077	0.000057
Aluminum	0.0000042	0.000084
Epoxy resin	0.000039	0.0009
Glass	0.0000017	0.000085
Iron	0.0000054	0.000019

Nickel	0.0000056	0.00124

The main principles of the LCA method were selected based on ideas from Imperiali et al.'s study [14].

LCIA's purpose is to provide extra details about a production system's LCI impacts so that their environmental significance can be better understood. The purpose of LCIA is to help individuals understand the significant potential ecological implications for manufacturing systems due to the findings of the LCI evaluation. LCIA should include the possible impact on "protected areas," including the biological landscape, human health, human-made environment, and resources. Many methods for assessing environmental consequences have improved in the previous ten years. In this study, ecological loads are measured using IMPACT 2002+. It demonstrates how to put a specified midpoint/damage strategy into action. It accomplishes this by connecting all types of LCI effects (main streams and other projects) to four damage categories: human health, ecological quality, climate change, and resources, via fifteen midway categories. The midway strategy is regarded as having less science and uncertainty behind it. The endpoint index, on the other hand, describes conservation zones, whereas the midway index demonstrates how inventory data and endpoints interact. The endpoint category is much less apparent, although it can produce obvious outcomes, making a selection more straightforward. Figure 3 depicts how the IMPACT 2002+ links the midpoints and endpoints impacts.

2.3. Evaluating the results

The life cycle interpretation is the final phase in the LCA process. This is where the consequences of LCI, LCIA, or both are summarised so that judgments, suggestions, and decisions consistent with the objectives can be made.

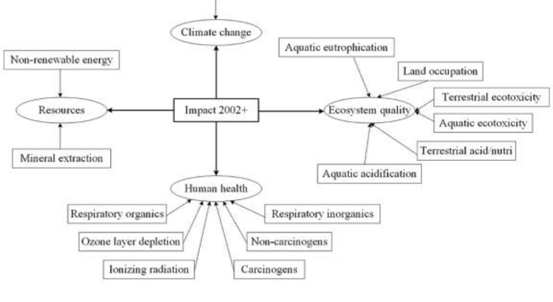


Figure 3. The relationship between the midpoint and endpoint impacts

2.4. Sensitivity analysis

Sensitivity analysis evaluates the uncertainties in the inputs to a quantitative system or model and their implications on the output of the model or system [30]. We can conduct a sensitivity analysis of the four damage categories by changing the inputs and the output factor by 10%. The four damage outcomes are addressed as dependent factors, while the independent variables include inputs of DC-DC circuit production and the energy used. An Excel 2019 spreadsheet is used to calculate parameters and conduct various analyses. SimaPro V8.2.3 software is also used to analyze LCA categorizations.

3. Results and Discussion

Simulation results in Simulink/MATLAB software are validated with a hardware prototype to confirm the theoretical computations of the proposed DDC. The simulation and prototype parameters and component specifications are defined in Table 3. The proposed non-isolated high gain voltage converter was assessed in the experimental platform indicated in Fig. 4. The experimental and simulation findings of the proposed DDC with D=0.65 in CCM operation have been shown in Fig. 5 to 14.

Table 3 Simulation and prototype parameters

Parameters	**Symbol**	**Values (unit)**
Output power	*Po*	220 (W)
Input voltage	*Vin*	20 (V)
Output voltage	*Vo*	228 (V)
Switching frequency	*fS*	50 (kHz)
Duty cycle	*D*	0.65
Inductors, L1, L2	*L1, L2*	240 (μH)
Boost capacitor and switched capacitors CB, C1, C2	*C1, C2, C3*	220 (μF)
Output capacitor, C0	*C0*	240 (μF)
MOSFET Switch	*Q*	IRFP260
Diodes D1, D2	*D1, D2*	MUR1515G
Diodes DC1, DC2, D0	*DC1, DC2, D0*	MUR1560G

Considering Figure 4, the proposed converter's voltage gain is higher than that of conventional single-switch DDCs such as boost, SEPIC, and converters proposed in [31-33].

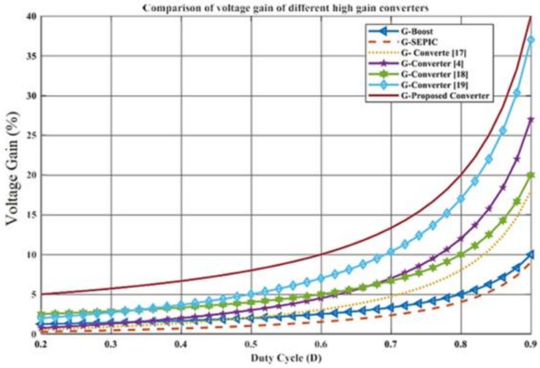


Figure 4. Curves of theoretical comparison of proposed converter and other converters at CCM operation

3.1. Results of LCA

Table 4 presents the midpoint impacts of the DC-DC converter in PV systems for power generation in nine scenarios. One scenario refers to the control, and the other eight refer to duty cycles from 0.2 to 0.9. According to the results, all the scenarios reduced the midpoint impacts by about 5 to 80% compared with the control. However, the variation trend by increasing the duty cycles is declining except for Non-carcinogens and Non-renewable energy potential. One of the main reasons is improving efficiency, reducing the raw materials and leaving less waste, and as a result, increasing power generation reliability and reducing environmental impacts. This process can reduce harmful ecological effects in the long and short term. It can also affect the policies developed in this field.

Imperiali et al. [14] obtained a similar finding when analyzing the environmental aspect of using an AC-DC converter. The main limitation was the need for comprehensive, high-quality ecological impact data on electronic components.

Table 4. The mid-point impacts of the DC-DC converter for power generation in PV systems

Impact category	Unit	Control	D 0.2	D 0.3	D 0.4	D 0.5	D 0.6	D 0.7	D 0.8	D 0.9
Carcinogens	kg C2H3Cl eq	9.61E-06	7.09E-06	6.69E-06	6.49E-06	6.48E-06	6.27E-06	6.09E-06	5.60E-06	5.57E-06
Non-carcinogens	kg C2H3Cl eq	10.10E-05	1.16E-05	1.09E-05	1.05E-05	1.05E-05	1.01E-05	9.83E-06	9.01E-06	8.92E-06
Respiratory inorganics	kg PM2.5 eq	8.77E-07	6.31E-07	5.99E-07	5.87E-07	5.81E-07	5.72E-07	5.57E-07	5.13E-07	5.12E-07
Ionizing radiation	Bq C-14 eq	6.64E-03	1.81E-03	1.72E-03	1.68E-03	1.67E-03	1.70E-03	1.66E-03	1.53E-03	1.52E-03
Ozone layer depletion	kg CFC-11 eq	7.81E-11	4.73E-11	4.35E-11	4.05E-11	4.17E-11	4.22E-11	4.04E-11	3.64E-11	3.53E-11
Respiratory organics	kg C2H4 eq	4.94E-07	2.06E-07	1.94E-07	1.87E-07	1.87E-07	1.79E-07	1.74E-07	1.60E-07	1.59E-07
Aquatic ecotoxicity	kg TEG water	8.64E-02	5.95E-02	5.59E-02	5.38E-02	5.40E-02	5.22E-02	5.06E-02	4.63E-02	4.59E-02
Terrestrial ecotoxicity	kg TEG soil	4.80E-02	1.89E-02	1.77E-02	1.70E-02	1.71E-02	1.65E-02	1.59E-02	1.46E-02	1.44E-02
Terrestrial acid/nutri	kg SO2 eq	8.24E-05	2.48E-05	2.36E-05	2.32E-05	2.30E-05	2.23E-05	2.18E-05	2.01E-05	2.02E-05
Land occupation	m2org.arable	7.06E-04	4.63E-04	4.44E-04	4.42E-04	4.33E-04	4.24E-04	4.15E-04	3.85E-04	3.88E-04
Aquatic acidification	kg SO2 eq	7.46E-06	3.81E-06	3.62E-06	3.55E-06	3.51E-06	3.43E-06	3.34E-06	3.08E-06	3.08E-06
Aquatic eutrophication	kg PO4 P-lim	4.81E-07	1.99E-07	1.89E-07	1.86E-07	1.84E-07	1.80E-07	1.75E-07	1.62E-07	1.62E-07
Global warming	kg CO2 eq	9.37E-04	8.13E-04	7.46E-04	6.91E-04	7.14E-04	6.58E-04	6.29E-04	5.68E-04	5.50E-04
Non-renewable energy	MJ primary	11.30E-02	1.21E-02	1.09E-02	9.83E-03	1.04E-02	9.30E-03	8.82E-03	7.86E-03	7.50E-03

Mineral extraction	MJ surplus	5.32E-05	2.32E-05	2.15E-05	2.02E-05	2.06E-05	1.95E-05	1.87E-05	1.70E-05	1.66E-05

Figure 5 presents the variation of the endpoint impacts affected by each treatment. On average, the lowest variation is related to D 0.2. Increasing the duty cycle reduces end-point environmental impacts. Adding a duty cycle significantly affects the efficiency of the DC-DC converter.

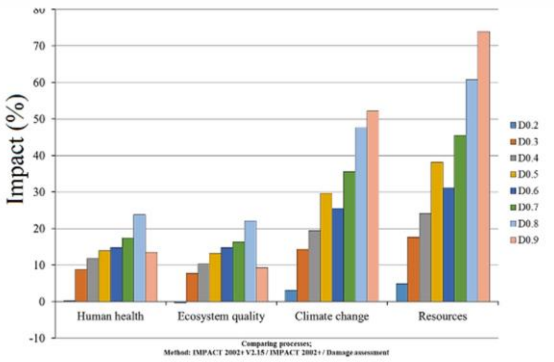


Figure 5. The end-point impacts of using DC-DC converter in power generation in PV systems

According to the results obtained from Figure 5, when considering the environmental aspects of using a non-isolated High Step-Up DC-DC converter for solar PV applications from an LCA perspective, several alternative scenarios can be regarded to evaluate the ecological impacts commented on. Here comprehensively are three alternative scenarios:

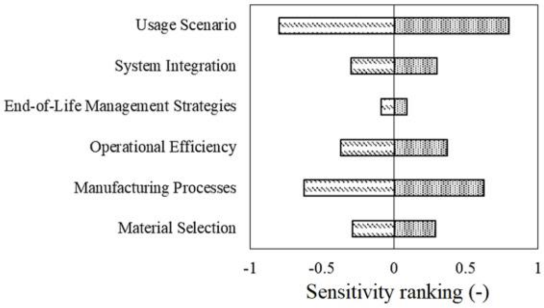
- Evaluation of the environmental consequences of using different materials and production techniques to produce a high non-isolated DC-DC converter: This choice of materials and manufacturing processes can significantly affect the ecological footprint. Evaluating alternative scenarios involving environmentally friendly materials, efficient production methods, and reduction of energy-intensive processes can provide insights into minimizing environmental impacts during the production phase.
- Investigate the environmental implications of end-of-life management strategies for high-voltage non-isolated DC-DC converters, including recycling, reuse, or responsible disposal. The disposal step is critical in determining the technology's overall sustainability. Comparing scenarios prioritizing recycling and reuse over conventional disposal methods allows for a comprehensive assessment of environmental impacts throughout the product's life cycle.
- Investigating the environmental benefits of integrating HSUNI DC-DC converter in solar PV systems with different levels of operational efficiency and energy storage capacities: The converter's performance is intricately linked to its integration into a solar PV system. Evaluating scenarios that consider different energy storage options, grid connectivity, and overall system efficiency will provide insights into the holistic environmental impact of this technology in practical applications.

These alternative scenarios enable a detailed assessment of the non-isolated High Step-Up DC-DC converter's environmental aspects and facilitate a more comprehensive understanding of its sustainability implications at different life cycle stages.

3.2. Results of sensitivity analysis

A sensitivity analysis was conducted to identify the most influential independent variables that impact the environment. According to Figure 6, Usage scenarios followed by manufacturing processes have the highest sensitivity score on endpoint impacts. These two parameters must be carefully considered in the design and using DC-DC converters.

Imperiali et al. [14] proposed that manufacturing processes are the most influential parameters in the environmental impacts of the AC-DC converter. This was a little different from the main priority of the present study. This difference can be due to the uncertainty of the inventory data.



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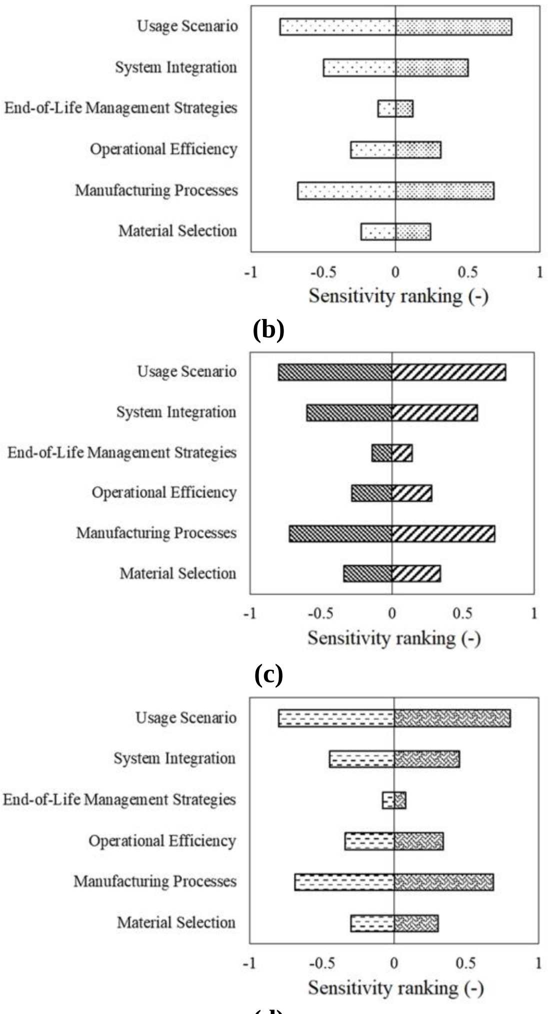

(b)

(c)

(d)

Figure 6. Sensitivity analysis of the effects of input on endpoint environmental impacts. a) Human health, b) Ecosystem quality, c) Climate change, d) Resources

3.3. Limitations and challenges of the study

The present study, while contributing valuable insights, has limitations and challenges. The accuracy of the LCA heavily relies on the availability and accuracy of data for each phase of the converter's life cycle. Obtaining precise data, especially for the extraction and manufacturing processes, can be challenging due to variations in manufacturing practices, supply chain complexities, and proprietary information. The lack of standardized data across the industry may introduce uncertainties in the assessment, impacting the reliability of the study's findings. This limitation is also emphasized by Imperiali et al. [14]. It should be noted that the number of studies conducted in the field is limited, and this causes a weak comparison of the findings for reliable discussion.

The study may face limitations in generalizability, as the environmental impact of the HSUNI DC-DC Converter can vary based on regional differences in energy mix, waste management practices, and environmental regulations. The study may not capture the nuances associated with different geographic locations, potentially limiting its applicability to a broader global context. Addressing this challenge requires careful consideration of regional variations and thoroughly examining the converter's life cycle in diverse environmental settings.

The study might encounter challenges in assessing the long-term environmental impacts and technological advancements. The rapid evolution of DC-DC converter technologies and the solar PV industry may render specific findings obsolete or less relevant. Anticipating future changes in manufacturing processes, materials, and end-of-life management practices is inherently challenging, and the study might not fully capture the environmental implications of emerging technologies or evolving industry standards.

The study's scope might not encompass all relevant environmental aspects, potentially overlooking specific environmental indicators or impacts that could be significant. For instance, the study might focus predominantly on greenhouse gas emissions and energy consumption, neglecting other critical factors like water usage, land occupation, or social aspects of sustainability. A more comprehensive assessment would require a broader consideration of multiple environmental dimensions, providing a holistic understanding of the HSUNI DC-DC Converter's ecological footprint.

While the study offers valuable insights into the environmental aspect of using the HSUNI DC-DC Converter for solar PV applications, addressing these limitations and challenges is essential for refining the findings' accuracy, applicability, and relevance.

4. Conclusions

The present study provides valuable insights into the sustainability of this technology from a LCA perspective. The following remarks have been obtained:

- Despite its contributions, the study has limitations and challenges that warrant consideration.
- The accuracy of the LCA hinges on data availability and precision, especially in the extraction and manufacturing phases.
- Challenges associated with obtaining standardized data across the industry may introduce uncertainties in the assessment.
- Regional variations in energy mix, waste management practices, and environmental regulations could constrain the study's generalizability. This underscores the need for a nuanced understanding of the converter's impact in diverse geographic contexts.
- The dynamic nature of technology and the solar PV industry poses challenges in predicting and capturing long-term environmental impacts and advancements.

The study may face limitations in adapting to rapid changes in manufacturing processes, materials, and end-of-life management practices. Moreover, the study's scope may not encompass all relevant environmental aspects, potentially overlooking critical factors beyond greenhouse gas emissions and energy consumption. Addressing these challenges is paramount for refining the study's findings and ensuring their relevance. Future research should strive for improved data accuracy, consider regional variations, and stay attuned to technological advancements. A more comprehensive assessment, encompassing a broader range of environmental indicators, will contribute to a more holistic understanding of the HSUNI DC-DC Converter's ecological footprint. In essence, while the study provides a valuable foundation for understanding the environmental aspects of the HSUNI DC-DC Converter, ongoing research efforts should build upon these insights, considering the evolving landscape of technology and striving for a more comprehensive and context-aware evaluation of its sustainability.

Nomenclature

AC	Alternative current
BC	Bidirectional converter
C	Capacitor
CO2	Carbon dioxide
D	Diode
DC	Direct current
DDC	DC-DC converter
EMS	Energy management strategy
FU	Functional unit
HESS	Hybrid energy storage system
HSUNI	High Step-Up Non-Isolated
L	Inductor
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MPPT	Maximum power point tracking
PV	Photovoltaic
SC	Supercapacitor
SEPIC	Single-Ended Primary Inductor Converter

References

1. Ranjana, M.S.B., N.S. Reddy, and R.K.P. Kumar. *A novel non-isolated high step-up DC-DC converters for photovoltaic applications*. In *2014 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2014]*. 2014. IEEE. https://doi.org/10.1109/ICCPCT.2014.7054955
2. Schmitz, L., D.C. Martins, and R.F. Coelho. (2018). High step-up nonisolated ZVS/ZCS DC-DC converter for photovoltaic thin-film module applications. *IEEE Journal of Emerging and Selected Topics in Power Electronics*. **7**(1): p. 565-575. https://doi.org/10.1109/JESTPE.2018.2830650
3. Li, W., et al. *A review of non-isolated high step-up DC/DC converters in renewable energy applications*. In *2009, the Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition*. 2009. IEEE.

https://doi.org/10.1109/APEC.2009.4802683

4. Koç, Y., Y. Birbir, and H. Bodur. (2022). Non-isolated high step-up DC/DC converters–An overview. *Alexandria Engineering Journal*. **61**(2): p. 1091-1132. https://doi.org/10.1016/j.aej.2021.06.071
5. Cao, Y., A novel step-up/step-down full-bridge DC-DC converter for distributed solar power applications. 2015, University of British Columbia. https://doi.org/10.14288/1.0166711
6. Saravanan, S. and N.R. Babu. (2017). A modified high step-up non-isolated DC-DC converter for PV application. *Journal of applied research and technology*. **15**(3): p. 242-249. https://doi.org/10.1016/j.jart.2016.12.008
7. Thangavelu, S. and P. Umapathy. (2021). Design of new high step-up DC-DC converter Topology for solar PV applications. *International Journal of Photoenergy*. **2021**: p. 1-11. https://doi.org/10.1155/2021/7833628
8. Maheswari, L. and N. Sivakumaran. (2020). An isolated single-switch high step-up DC/DC converter with a three-winding transformer for solar photovoltaic applications. *Electrical Engineering*. **102**: p. 1383-1392. https://doi.org/10.1007/s00202-020-00959-y
9. Ramu, S.K., et al. (2024). Enhanced energy management of DC microgrid: Artificial neural networks-driven hybrid energy storage system integrating bidirectional DC-DC converter. *Journal of Energy Storage*. **88**: p. 111562. https://doi.org/10.1016/j.est.2024.111562
10. Samiulla, S.M. and K. Rachananjali. (2024). A novel development of a new single switch inductor coupled DC-DC converter for PV system with two-leg inverter. *Scientific Reports*. **14**(1): p. 10734. https://doi.org/10.1038/s41598-024-61637-8
11. Satyanarayana, K.V. and R. Maurya. (2024). Unified control of high gain DC-DC converter for PV-battery hybrid system in standalone and DC-microgrid applications. *Journal of Energy Storage*. **88**: p. 111475. https://doi.org/10.1016/j.est.2024.111475
12. Rajamani, M., et al. (2024). Photovoltaic-Based Dual Output DC-DC Converter Using Gravitational Search Algorithm-Tuned PI and Sliding Mode Controllers. *Arabian Journal for Science and Engineering*. p. 1-19. https://doi.org/10.1007/s13369-024-08962-2
13. Mizani, A., et al. (2024). A new efficiency non‐isolated DC‐DC converter with a combination of step‐up techniques. *International Journal of Circuit Theory and Applications*. https://doi.org/10.1002/cta.4074
14. Imperiali, L., et al. *Multi-Objective Minimization of Life-Cycle Environmental Impacts of Three-Phase AC-DC Converter Building Blocks*. in *2024 IEEE Applied Power Electronics Conference and Exposition (APEC)*. 2024. IEEE. https://doi.org/10.1109/APEC48139.2024.10509190
15. Vighetti, S., J.-P. Ferrieux, and Y. Lembeye. (2011). Optimization and design of a cascaded DC/DC converter devoted to grid-connected photovoltaic systems. *IEEE Transactions on Power Electronics*. **27**(4): p. 2018-2027. https://doi.org/10.1109/TPEL.2011.2167159
16. Marodkar, M., et al. *Design and simulation of DC-DC converters for Photovoltaic system based on MATLAB*. in *2015 International Conference on Industrial Instrumentation and Control (ICIC)*. 2015. IEEE. https://doi.org/10.1109/IIC.2015.7150983
17. Palanisamy, R., et al. (2019). Simulation of various DC-DC converters for photovoltaic systems. *International Journal of Electrical and Computer Engineering*. **9**(2): p. 917. https://doi.org/10.11591/ijece.v9i2.pp917-925
18. Mohamed, H., et al. *Design, control, and performance analysis of DC-DC boost converter for stand-alone PV system*. in *2016 Eighteenth International Middle East Power Systems Conference (MEPCON)*. 2016. IEEE. https://doi.org/10.1109/MEPCON.2016.7836878
19. Walker, G.R. and J.C. Pierce. *Photovoltaic DC-DC module integrated converter for novel cascaded and bypass grid connection*

topologies—Design and optimization. in *2006 37th IEEE Power Electronics Specialists Conference*. 2006. IEEE. https://doi.org/10.1109/pesc.2006.1712242

20. Hasaneen, B. and A.A.E. Mohammed. *Design and simulation of DC/DC boost converter*. In *2008, the 12th International Middle-East Power System Conference*. 2008. IEEE. https://doi.org/10.1109/MEPCON.2008.4562340
21. Navamani, J.D., T. Padhi, and A. Kumari. (2022). Analysis of a family of step-up converters for PV application with lifecycle assessment. *Materials Today: Proceedings*. **50**: p. 218-224. https://doi.org/10.1016/j.matpr.2021.05.310
22. Bansal, S., L.M. Saini, and D. Joshi. *Design of a DC-DC converter for the photovoltaic solar system*. in *2012 IEEE 5th India International Conference on Power Electronics (IICPE)*. 2012. IEEE. https://doi.org/10.1109/IICPE.2012.6450508
23. ISO, I.J.E.M.-L.C.A.-P. and F.I.O.f. Standardization. (2006). ISO 14040 international standard.
24. Yılmaz, E., H. Arslan, and A. Bideci. (2019). Environmental performance analysis of insulated composite facade panels using life cycle assessment (LCA). *Construction Building Materials*. **202**: pp. 806-813. https://doi.org/10.1016/j.conbuildmat.2019.01.057
25. La Rosa, A., et al. (2016). Recycling treatment of carbon fiber/epoxy composites: Materials recovery, characterization, and environmental impacts through life cycle assessment. *Composites Part B: Engineering*. **104**: p. 17-25. https://doi.org/10.1016/j.compositesb.2016.08.015
26. Rebitzer, G., et al. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment international*. **30**(5): p. 701-720. https://doi.org/10.1016/j.envint.2003.11.005
27. Van den Heede, P. and N. De Belie. (2012). Environmental impact and life cycle assessment (LCA) of traditional and 'green concrete Literature review and theoretical calculations. *Cement Concrete Composites*. **34**(4): p. 431-442. https://doi.org/10.1016/j.cemconcomp.2012.01.004
28. Kylili, A., E. Christoforou, and P.A. Fokaides. (2016). Environmental evaluation of biomass pelleting using life cycle assessment. *Biomass Bioenergy*. **84**: p. 107-117. https://doi.org/10.1016/j.biombioe.2015.11.018
29. Cherubini, F., S. Bargigli, and S. Ulgiati. (2009). Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant, and incineration. *Energy*. **34**(12): p. 2116-2123. https://doi.org/10.1016/j.energy.2008.08.023
30. Saltelli, A., et al., *Global sensitivity analysis: the primer*. 2008: John Wiley & Sons. https://doi.org/10.1002/9780470725184.ch6
31. Banaei, M.R. and S.G. Sani. (2018). Analysis and implementation of a new SEPIC-based single-switch buck-boost DC-DC converter with the continuous input current. *IEEE transactions on power electronics*. **33**(12): p. 10317-10325. https://doi.org/10.1109/TPEL.2018.2799876
32. Maheri, H.M., et al. (2017). High step-up DC-DC converter with minimum output voltage ripple. *IEEE Transactions on Industrial Electronics*. **64**(5): p. 3568-3575. https://doi.org/10.1109/TIE.2017.2652395
33. Wu, G., X. Ruan, and Z. Ye. (2014). Nonisolated high step-up DC-DC converters are adopting switched-capacitor cells. *IEEE Transactions on Industrial Electronics*. **62**(1): p. 383-393. https://doi.org/10.1109/TIE.2014.2327000