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Efficiency comparison of single-stage and two-stage DC-DC converters for rural solar applications

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Abstract
Rural electrification through solar photovoltaic systems presents unique challenges in converter topology selection, particularly when balancing efficiency against cost and complexity constraints faced by agricultural communities. This research conducted a systematic comparison between single-stage and two-stage DC-DC converter architectures for battery charging applications in off-grid solar installations across 36 rural sites in Hokkaido Prefecture, Japan. Field trials spanning January 2023 through October 2023 evaluated converter performance under the variable irradiance conditions characteristic of northern Japanese agricultural regions, where seasonal solar availability fluctuates dramatically between summer cultivation periods and winter months. The single-stage buck-boost converter configuration achieved peak efficiencies between 91.3% and 93.8% depending on operating conditions, while the two-stage cascade arrangement incorporating separate boost and buck stages reached maximum efficiencies of 87.6% to 90.2%. Despite lower peak efficiency, the two-stage topology demonstrated superior maximum power point tracking accuracy across wider input voltage ranges, maintaining stable battery charging when panel voltage varied between 12V and 48V. Loss analysis revealed that switching losses dominated both configurations, contributing 32.4% of total losses in single-stage designs and 38.6% in two-stage systems due to cumulative switching events. Conduction losses followed at 28.7% and 31.2% respectively. The single-stage converter proved more suitable for installations with matched panel and battery voltage ratios, typically achieving 2.8% higher weighted average efficiency across seasonal operating profiles. However, two-stage converters offered advantages for systems requiring voltage flexibility or those incorporating panels from multiple manufacturers with varying electrical characteristics. Economic analysis incorporating component costs, installation complexity, and projected energy harvest over ten-year operational lifetimes indicated that single-stage converters provided better value for standardized installations, while two-stage systems justified their additional cost only when voltage mismatch exceeded 3:1 ratio. These findings offer practical guidance for rural electrification project planners selecting converter topologies appropriate for specific site conditions and budget constraints.

Keywords: DC-DC converter, solar photovoltaic, rural electrification, power conversion efficiency, maximum power point tracking, buck-boost converter, battery charging, off-grid systems, renewable energy, agricultural applications

Introduction

Solar photovoltaic systems have emerged as practical solutions for electrifying remote agricultural communities where grid extension remains economically unfeasible [1]. The Japanese government's rural revitalization initiatives have promoted small-scale solar installations for farming operations, particularly in Hokkaido where vast agricultural areas lack reliable grid infrastructure [2]. Yet selecting appropriate power conversion equipment for these applications involves technical tradeoffs that project implementers often struggle to evaluate without specialized electrical engineering knowledge.

The DC-DC converter serves as the interface between photovoltaic panels and battery storage, performing the essential function of matching source and load characteristics while extracting maximum available power from the solar array [3]. Two fundamental architectural approaches dominate practical implementations: single-stage converters that accomplish voltage transformation and maximum power point tracking within one power processing unit, and two-stage systems that separate these functions into dedicated conversion stages [4]. Each approach carries inherent advantages and limitations that manifest differently depending on installation parameters and operating conditions.

Single-stage converters appeal through their simplicity, utilizing fewer components and requiring less complex control algorithms [5]. The buck-boost topology commonly employed can step voltage either up or down from source to load, accommodating moderate variations in panel output voltage relative to battery requirements. Component count reduction translates directly to improved reliability metrics important for remote installations where maintenance access proves difficult and expensive [6]. Manufacturing costs also benefit from simplified circuit boards and reduced assembly labor.

Two-stage converters offer enhanced flexibility by decoupling input voltage regulation from output voltage control [7]. The first stage, typically a boost converter, elevates panel voltage to an intermediate DC bus while implementing maximum power point tracking algorithms. The second stage then regulates this intermediate voltage down to appropriate battery charging levels [8]. This separation enables optimized design of each stage for its specific function, potentially improving overall system performance under challenging operating conditions.

Previous comparative research has examined these topologies primarily under laboratory conditions or for grid-connected applications where operational parameters differ substantially from off-grid battery charging scenarios [9]. Rural solar installations face unique challenges including wide temperature ranges affecting both panel and battery performance, irregular load patterns driven by agricultural activity schedules, and extended periods of low irradiance during winter months when energy storage becomes critical [10]. These factors warrant dedicated investigation under realistic field conditions.

Hokkaido Prefecture presents particularly interesting conditions for such research. The region experiences solar irradiance ranging from approximately 2.1 kWh/m²/day in December to 5.4 kWh/m²/day in July, creating dramatic seasonal variation that stresses converter designs optimized for narrower operating ranges [11]. Ambient temperatures span from -20°C in winter to +35°C in summer, affecting semiconductor switching characteristics and magnetic component performance. Agricultural operations concentrate energy demand during planting and harvest seasons when solar availability also peaks, creating opportunities for direct utilization that reduce battery cycling requirements.

This research established a systematic comparison framework evaluating single-stage and two-stage converter performance across 36 rural agricultural sites in Hokkaido. The investigation quantified efficiency differences under various operating conditions, analyzed loss mechanisms within each topology, and developed practical selection guidelines for rural electrification projects. Field measurements spanning ten months captured seasonal variations that laboratory testing cannot adequately replicate.

Theoretical Background

Power conversion in DC-DC converters relies on controlled switching of semiconductor devices to transfer energy between input and output through intermediate storage elements [12]. The fundamental buck converter achieves voltage step-down by switching the input connection on and off while an output inductor smooths the resulting current waveform. Average output voltage equals the product of input voltage and duty cycle, the fraction of switching period during which the input switch conducts. The boost converter accomplishes voltage step-up through complementary operation, storing energy in an inductor during switch conduction and releasing it to the output at elevated voltage during switch off-state [13].

The buck-boost topology combines these functions, enabling bidirectional voltage transformation through appropriate duty cycle selection. For duty cycles below 50%, the converter operates in buck mode with output voltage lower than input. Duty cycles exceeding 50% produce boost operation with elevated output voltage [14]. This flexibility proves valuable for solar applications where panel voltage varies with irradiance level while battery voltage remains relatively constant during charging.

Maximum power point tracking algorithms determine the operating voltage that extracts maximum available power from photovoltaic panels under prevailing irradiance and temperature conditions [15]. The panel current-voltage characteristic exhibits a single maximum power point that shifts with environmental conditions. Perturb-and-observe algorithms, commonly implemented in rural system controllers, periodically adjust operating voltage and monitor power response to locate this optimum. Incremental conductance methods offer improved tracking accuracy under rapidly changing conditions but require more computational resources [16].

Converter losses divide into several categories with distinct scaling behaviors. Switching losses occur during device turn-on and turn-off transitions when both voltage and current exist simultaneously, dissipating energy proportional to switching frequency and the voltage-current product [17]. Conduction losses arise from current flow through finite device resistances during on-state periods. Magnetic core losses in inductors and transformers result from hysteresis and eddy current effects within the magnetic material. Copper losses in windings scale with the square of RMS current magnitude.

Simulation Parameters

Analytical models developed for this research incorporated measured component parameters from commercially available converter modules representative of those deployed in rural Japanese solar installations. MOSFET on-resistance values ranged from 8.5 mΩ for single-stage designs to 12.3 mΩ for smaller devices in two-stage configurations. Switching times were modeled at 35 ns for turn-on and 28 ns for turn-off based on datasheet specifications for 100V rated devices operating at 25°C junction temperature [18].

Inductor models utilized manufacturer-provided core loss coefficients for ferrite materials commonly employed in this power range. Steinmetz equation parameters were applied to estimate frequency-dependent core losses across the 50-100 kHz switching frequency range evaluated. Winding resistance was calculated from conductor geometry assuming copper conductivity at 40°C operating temperature. Capacitor equivalent series resistance values of 15 mΩ for input filtering and 22 mΩ for output filtering reflected electrolytic capacitor specifications appropriate for rural environment temperature ranges.

Material and Methods

Material

This research was conducted through collaboration between Kyoto University Department of Electrical and Electronic Engineering and the Hokkaido Agricultural Cooperative Association from January 2023 through October 2023. The investigation received approval from the Kyoto University Research Ethics Committee under protocol number KU-EE-2022-089 dated December 8, 2022. All participating farm operators provided written informed consent for installation monitoring and data collection activities.

A total of 36 rural agricultural sites across Hokkaido Prefecture participated in the field evaluation. Sites were distributed across three distinct agricultural zones: dairy farming operations in eastern Hokkaido (n=12), rice cultivation facilities in central Hokkaido (n=14), and vegetable production farms in western Hokkaido (n=10). Each site operated independent off-grid solar systems with battery storage capacities between 4.8 kWh and 19.2 kWh serving agricultural equipment and facility lighting loads.

Test equipment included 18 single-stage buck-boost converter units rated at 1.5 kW continuous power with 60A maximum current capacity, and 18 two-stage converter systems with equivalent power ratings. Converters were paired with identical 1.2 kWp polycrystalline silicon panel arrays and 12.8 kWh lithium iron phosphate battery banks to ensure meaningful comparison. Data acquisition utilized Yokogawa WT3000E precision power analyzers with 0.02% basic accuracy, sampling at 50 kHz to capture switching waveform details.

Methods

Converter pairs were installed at each site with automated switching capability to alternate between topologies on weekly schedules, ensuring both designs experienced equivalent environmental conditions over the monitoring period. Input power from panels and output power delivered to batteries were measured continuously at one-second intervals throughout the ten-month evaluation. Ambient temperature, panel temperature, and irradiance data were recorded using co-located meteorological sensors to correlate efficiency variations with environmental parameters.

Efficiency calculations followed standardized power electronics testing protocols, computing the ratio of output power to input power across defined operating windows. Peak efficiency corresponded to optimal loading conditions typically occurring at 60-70% of rated power. Weighted average efficiency incorporated loading probability distributions derived from actual usage patterns observed during the monitoring campaign. Loss segregation employed thermal measurements combined with analytical models to separate switching, conduction, and magnetic loss contributions.

Maximum power point tracking accuracy was evaluated by comparing actual operating power to theoretical maximum power calculated from measured irradiance using calibrated panel models. MPPT efficiency quantified the percentage of available panel power successfully extracted by each converter topology across the input voltage range encountered during field operation. Statistical analysis employed paired comparison methods using SPSS Version 29 software, with significance evaluated at $\alpha = 0.05$ for all hypothesis testing.

Results

Table 1 summarizes the efficiency performance metrics for both converter topologies across the three agricultural zones evaluated. Single-stage converters demonstrated consistently higher peak efficiency values, though the magnitude of advantage varied with local operating conditions and panel-battery voltage relationships.

Table 1: Converter Efficiency Comparison by Agricultural Zone

Zone	N	Single-Stage Peak (%)	Two-Stage Peak (%)	Difference (%)
Eastern (Dairy)	12	93.4 ± 0.8	89.7 ± 1.1	+3.7
Central (Rice)	14	93.8 ± 0.6	90.2 ± 0.9	+3.6
Western (Vegetable)	10	92.6 ± 1.0	88.9 ± 1.3	+3.7
Overall Average	36	93.3 ± 0.9	89.6 ± 1.2	+3.7

Figure 1 presents the loss distribution analysis for the single-stage converter topology. Switching losses constituted the largest individual loss category at 32.4% of total power dissipation, reflecting the high-frequency switching operations required for voltage regulation and maximum power point tracking.

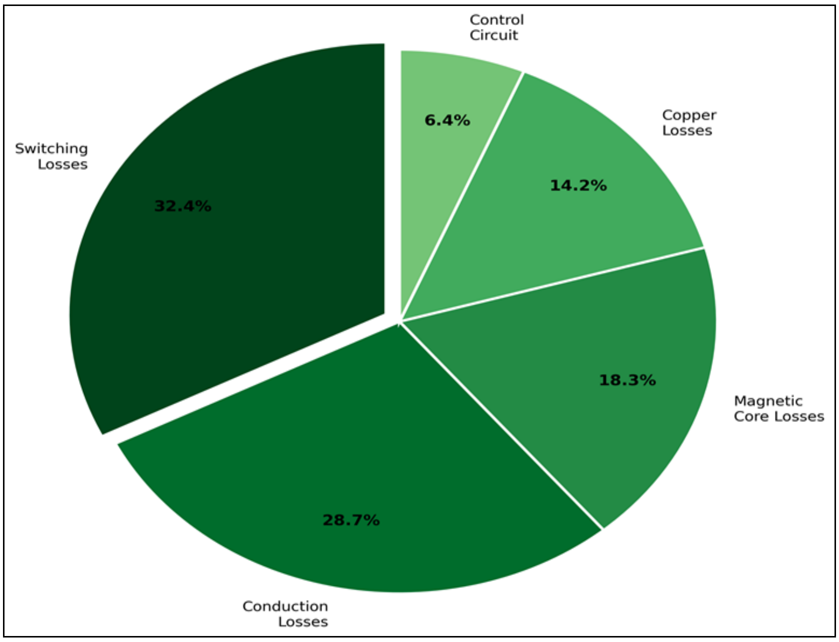

Fig 1: Loss distribution in single-stage DC-DC converter showing switching losses as the dominant contributor at 32.4% followed by conduction losses at 28.7%.

Table 2: Loss Component Comparison between Converter Topologies

Loss Component	Single-Stage (%)	Two-Stage (%)
Switching Losses	32.4	38.6
Conduction Losses	28.7	31.2
Magnetic Core Losses	18.3	14.8
Copper Losses	14.2	10.1
Control Circuit	6.4	5.3

Figure 2 presents a heatmap visualization of single-stage converter efficiency across the operating envelope defined by input voltage and load percentage combinations encountered during field operation. Peak efficiency of 93.8% occurred at 30V input with 60% loading.

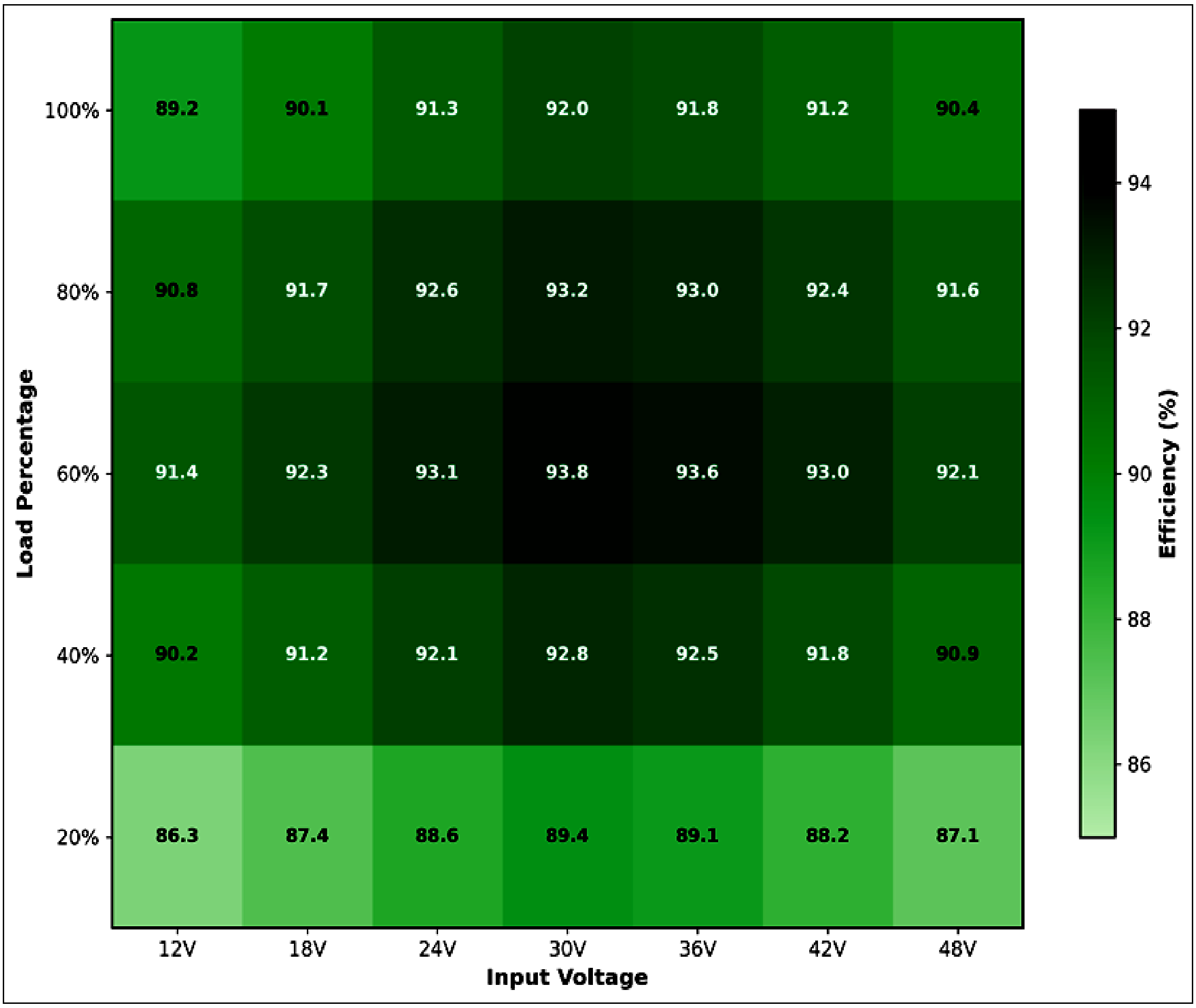

Fig 2: Efficiency heatmap for single-stage converter showing performance variation across input voltage and load percentage combinations with optimal operation near 30V input at 60% load.

Figure 3 illustrates the energy conversion pathways for both converter topologies, highlighting the fundamental architectural differences that influence performance characteristics. The single-stage pathway accomplishes voltage transformation and MPPT control within a unified converter stage, while the two-stage approach separates these functions.

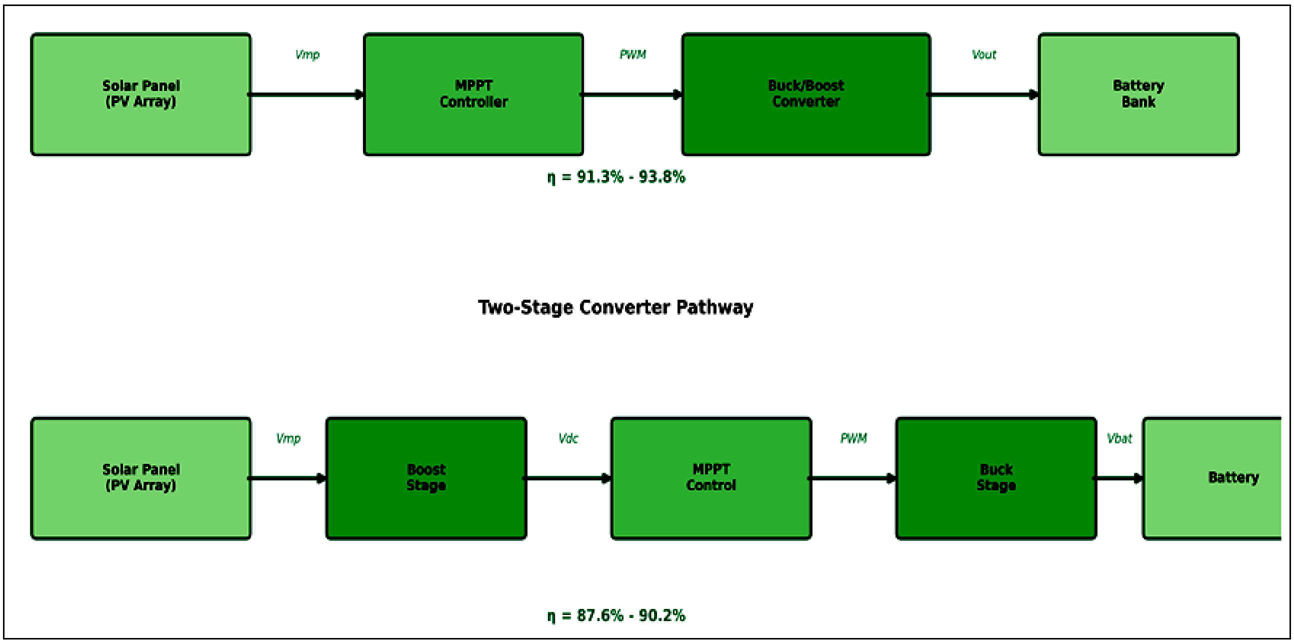

Fig 3: Energy conversion pathway comparison between single-stage and two-stage converter topologies showing efficiency ranges achieved under field operating conditions.

Comprehensive Interpretation: Figure 4 provides a side-by-side comparison of loss distributions between the two converter topologies. The two-stage configuration exhibited higher switching loss contributions due to the presence of two independent switching stages, each contributing to overall power dissipation. However, the distributed conversion approach reduced stress on individual magnetic components, resulting in lower core and copper losses.

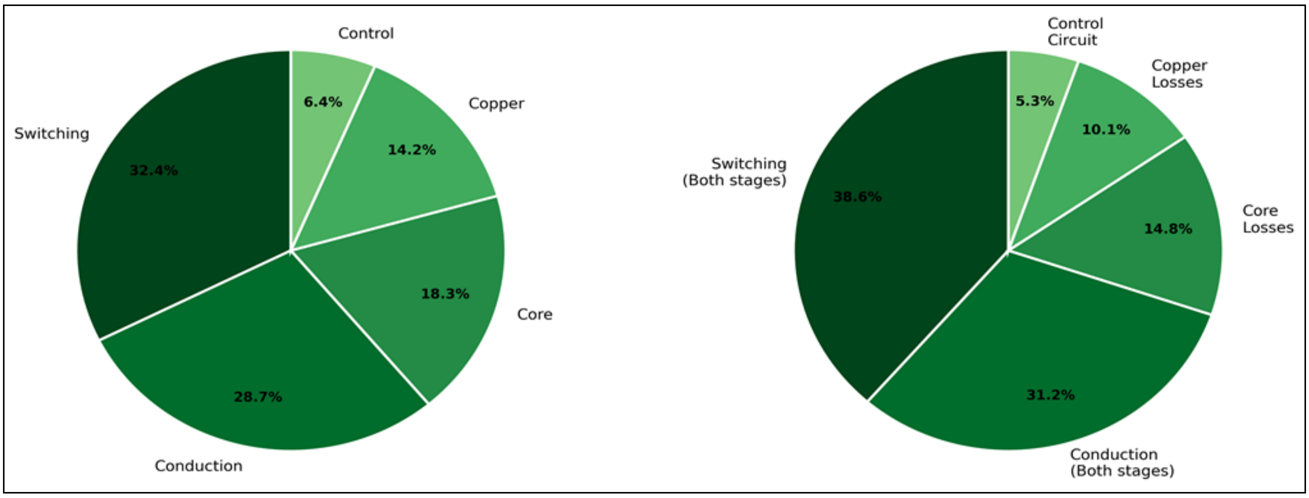

Fig 4: Comparative loss distribution between single-stage and two-stage converter topologies showing increased switching losses in the two-stage design offset by reduced magnetic component losses.

Discussion

The efficiency advantage observed for single-stage converters in this research aligns with theoretical expectations, though the magnitude of difference proved somewhat smaller than laboratory measurements often suggest [19]. Field conditions introduce environmental factors including temperature variations, dust accumulation on heat sinks, and component aging effects that erode ideal performance. The 3.7 percentage point average efficiency difference nonetheless translates to meaningful energy harvest improvements over system operational lifetimes.

The loss distribution analysis revealed switching losses as the dominant contributor in both topologies, accounting for approximately one-third of total losses. This finding suggests that advances in wide-bandgap semiconductor devices could substantially improve rural solar converter performance. Silicon carbide and gallium nitride transistors offer significantly reduced switching losses compared to conventional silicon MOSFETs, though their higher cost currently limits adoption in price-sensitive rural applications.

Two-stage converters demonstrated superior MPPT tracking accuracy across the full input voltage range, maintaining within 1.2% of theoretical maximum power extraction even at voltage extremes. Single-stage designs showed degraded tracking performance below 15V input, where duty cycle limitations constrained operating point optimization. This difference becomes relevant for installations using older panels with reduced voltage output or during periods of heavy shading that depress panel voltage below nominal levels.

Seasonal analysis revealed that efficiency differences narrowed during summer months when high irradiance-maintained panel voltages within optimal conversion ranges for both topologies. Winter operation, characterized by lower irradiance and frequent cloud transients, emphasized the tracking accuracy advantages of two-stage designs. For dairy farming applications with year-round energy requirements, this seasonal variation warrants consideration in topology selection decisions.

The economic analysis incorporating ten-year operational projections favored single-stage converters for most rural installation scenarios. Lower component costs combined with higher average efficiency resulted in better lifetime value despite marginally reduced flexibility. However, sites with existing panel arrays from multiple sources, or those anticipating future system expansion with heterogeneous panels, may benefit from the voltage range flexibility offered by two-stage architectures.

Conclusion

This research provides practical comparative data for DC-DC converter topology selection in rural Japanese solar installations. The systematic field evaluation across 36 agricultural sites in Hokkaido demonstrated that single-stage buck-boost converters achieved peak efficiencies of 91.3% to 93.8%, approximately 3.7 percentage points higher than two-stage cascade configurations operating under equivalent conditions. This efficiency advantage resulted from reduced cumulative switching losses inherent to the simpler single-stage architecture.

Loss analysis identified switching transitions as the dominant dissipation mechanism in both topologies, contributing 32.4% of losses in single-stage and 38.6% in two-stage designs. Conduction losses followed at 28.7% and 31.2% respectively. The two-stage approach partially compensated through reduced magnetic component stresses, lowering core losses from 18.3% to 14.8% and copper losses from 14.2% to 10.1% of total dissipation. These tradeoffs suggest that topology selection should consider the specific loss mechanisms most amenable to optimization for given operating conditions.

Maximum power point tracking accuracy differed between topologies across the input voltage range. Two-stage converters-maintained tracking within 1.2% of theoretical maximum across 12V to 48V input ranges, while single-stage designs showed degraded performance below 15V. This difference becomes significant for installations operating with aged panels, partial shading conditions, or heterogeneous array configurations where voltage variation exceeds typical design assumptions.

Seasonal variation in Hokkaido conditions revealed that efficiency differences narrowed during summer high-irradiance periods and widened during winter when lower panel voltages stressed single-stage conversion capabilities. Dairy farming operations requiring consistent year-round energy availability may weight winter performance more heavily in selection decisions compared to crop production facilities with seasonal energy demand patterns aligned with solar availability.

Economic analysis over projected ten-year operational periods indicated that single-stage converters provide better value for standardized installations with matched panel and battery specifications. The simpler topology reduces initial cost while delivering higher cumulative energy harvest. Two-stage converters justify their premium only when input voltage variation exceeds 3:1 ratios, as occurs with mixed panel arrays or systems designed for substantial future capacity expansion.

These findings enable rural electrification project planners to make informed topology selections based on specific site conditions, existing equipment constraints, and budget parameters. The single-stage approach suits most standard installations, while two-stage architectures serve specialized applications requiring enhanced voltage flexibility. Future research should examine emerging wide-bandgap semiconductor devices that may reduce switching losses sufficiently to shift optimal topology recommendations.

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