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COMPARATIVE CUMULATIVE ENERGY DEMAND ANALYSIS OF TALL SPINDLE AND GUYOT TRAINING SYSTEMS IN MOUNTAIN APPLE PRODUCTION

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Abstract: In modern apple cultivation, the choice of orchard training system is a critical factor that directly influences yield, fruit quality, resource efficiency, and energy performance, especially in mountainous regions, where topographic constraints increase operational intensity. This study evaluated the energy performance of two orchard training systems in the mountainous region of Northern Italy: the conventional Tall Spindle (TS) and innovative Guyot (GS) systems. Using the Cumulative Energy Demand (CED) framework, the analysis quantified primary energy intensity across a "cradle-to-farm-gate" system boundary, with all inputs normalized to a functional unit of 1 kg of fresh apples. The results show that the Guyot system reduces the total cumulative energy demand by 22.9%, from 1.44 MJ kg^{-1} for TS to 1.11 MJ kg^{-1} for GS. This reduction stems primarily from decreased electricity use (-49.5%) and lower energy embodied in machinery (-66.9%) due to the narrow canopy, which minimizes the need for elevated harvesting platforms. However, GS requires greater embodied energy in the trellis infrastructure (+18.4%) owing to its narrow-row design. Despite these gains, both systems remain heavily reliant on non-renewable fossil sources, which account for over 93% of the total demand, with diesel and fertilizers as persistent energy hotspots. The study concluded that architectural redesign toward simplified narrow-canopy structures is a primary lever for improving energy efficiency in mountain orchards, enabling significant energy savings without compromising yield. Therefore, future research and implementation should focus on integrating architectural innovation with precision input management and renewable energy adoption to further enhance resource efficiency and advance sustainable intensification in mountain agriculture.

Keywords: cumulative energy demand, apple cultivation, tree architecture, mountain agriculture

1. Introduction

In the last decades, modern apple cultivation has increasingly focused on production-oriented training systems designed to maximize both yield and fruit quality. In response to economic pressure and market demand, apple cultivation has led to the widespread adoption of high-density orchards (Lordan et al., 2018). These systems facilitate mechanization, improve efficiency, and enhance productivity. However, they also induce shifts in energy dynamics, such as higher initial investments in infrastructure and potentially reduced orchard lifespans, thus presenting complex sustainability trade-offs (Lordan et al.,

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2018; Waleed Fouad, 2021). The intensification and expansion of production within modern agricultural systems have led to increased energy consumption, further challenging the sustainability of current practices and increasing environmental concerns (Molaee Jafrodi et al., 2022). The structural design of orchards, particularly the training system, directly influences operational energy use, including labor requirements, machinery duty cycles and input application efficiency. Given the direct link between structural design and resource use, a detailed understanding of the primary energy demand associated with different orchard architectures is essential for advancing energy-efficient and sustainable fruit production.

In mountainous regions, such as the Italian Alps, where this study was conducted, the Tall Spindle (TS) system represents the regional standard, characterized by a three-dimensional conical canopy. While this system is productive, it presents challenges in terms of canopy management, labor efficiency, and mechanization access on sloped terrain. In response, the innovative Guyot system was developed as a two-dimensional fruit wall architecture to simplify canopy access, improve management efficiency, and enhance mechanization potential (Dorigoni, 2016). However, whether this architectural redesign translates into measurable energy savings under mountain conditions remains unquantified, as prior research has focused predominantly on agronomic outcomes rather than on energy performance.

To address this gap, this study utilized the Cumulative Energy Demand (CED) methodological framework. CED provides a robust approach for quantifying the total primary energy consumed throughout a product's life cycle, capturing both direct (e.g., electricity and fuel) and indirect energy (e.g., embodied in agrochemicals and equipment) while differentiating between fossil and renewable sources (Huijbregts et al., 2010; Zoli & Bacenetti, 2025). As most environmental impacts are associated with primary energy consumption, CED is an effective screening tool for evaluating system-level energy performance (Huijbregts et al., 2010).

Therefore, this study applied a Cumulative Energy Demand analysis to compare the Tall Spindle and Guyot training systems within the specific context of mountain apple production. By evaluating these architectural models from a life-cycle energy perspective, this study provides the first dedicated assessment of primary energy demand across different energy source categories. The analysis quantifies the energy trade-offs between infrastructure and operations, offering data-driven insights to inform orchard design and advance sustainable intensification in mountain agriculture.

2. Materials and Methods

2.1 Case Study Area and Training System Architecture

The study was conducted in the Non-Valley in the Trentino-Alto Adige region of Northern Italy, a territory representative of intensive mountain apple production. The research area is characterized by steep terrain, where crop cultivation practices are strongly influenced by slope and altitude. To assess the energy intensity of different high-density orchard practices, the analysis focused on two distinct apple orchard training systems: the established Tall Spindle and the innovative Guyot system, as illustrated in Figure 1.

The first configuration, the Tall Spindle (TS) system, is the established regional standard, characterized by a three-dimensional (3D) conical canopy supported by a central leader tree, reaching 4 m in height. This system is maintained at a high planting density of 3,906 trees ha^{-1}, with a row spacing of 3.2 m and a narrow between-plant spacing of 0.8 m (Figure 1a). The TS system is designed for rapid establishment and high productivity, achieving an annual average yield of 52.54 t ha^{-1}.

In contrast, the Guyot (GS) system represents an innovative architectural simplification by transitioning the orchard into a narrow two-dimensional (2D) fruit wall canopy. This configuration is specifically obtained by training multiple vertical leaders from a horizontal cord, which restricts the tree height to 3.0 m and canopy depth to less than 40 cm. The GS operates at a lower density of 2,899 trees ha^{-1} with reduced row spacing of 2.3 m and wider between-plant spacing of 1.5 m (Figure 2b). The Guyot system requires 2-3 years to establish its structural framework, specifically to fill the space between the horizontal cordons and the fruiting top (Bortolotti et al., 2022; Dorigoni & Micheli, 2019). Despite this, GS maintains high productivity, with a comparable annual average yield of 51.65 t ha^{-1}.

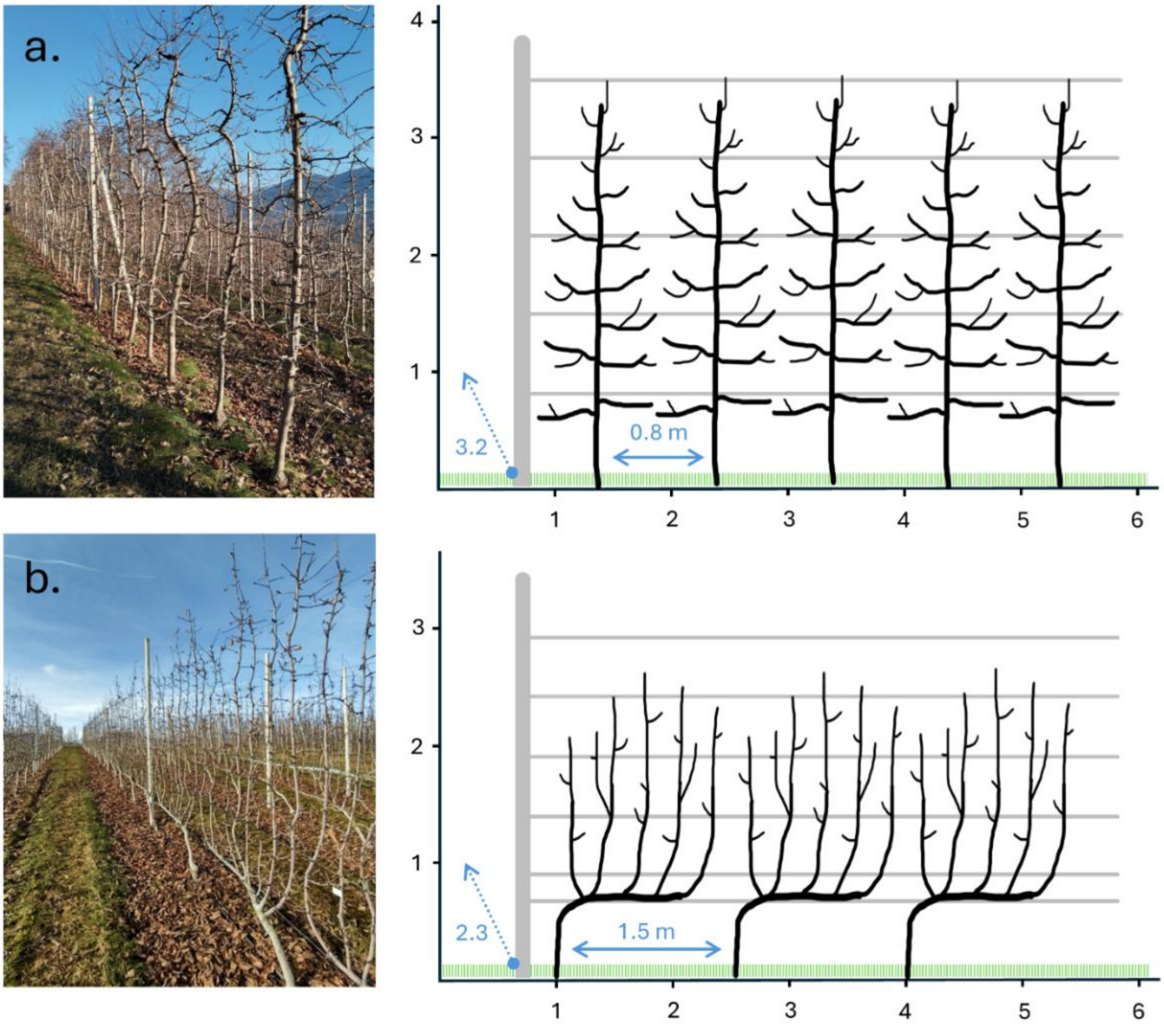

Figure 1. Architectural and structural configurations of the apple-training systems were studied. (a) Tall Spindle (TS). The solid arrow lines indicate plant spacing, and the dotted lines indicate row spacing.

2.2 System Boundaries and Functional Unit

The primary goal of this study was to quantify and compare the Cumulative Energy Demand (CED) of two distinct apple training systems, the established Tall Spindle (TS) and the innovative Guyot (GS), to identify strategies for improving energy efficiency in mountain orchards. The analysis utilized a "cradle-to-farm-gate" system boundary, encompassing all energy inputs from raw material extraction through the nursery stage, orchard establishment, and annual management, up to the delivery of fresh apples to the warehouse. Subsequent stages (e.g., post-harvest storage and packaging) and sales processes were excluded from the scope, as the primary aim was to identify strategies for improving production management. The environmental burden of capital goods (such as trellises, irrigation infrastructure, and nursery stocks) was annualized over the 20-year expected lifespan of the orchard. The functional unit (FU) was defined as 1 kg of fresh apples at the farm gate, allowing for a direct comparison of energy intensity relative to production performance across different systems.

2.3 Data Collection and Life Cycle Inventory (LCI)

The Life Cycle Inventory was developed by integrating primary, site-specific foreground data with established background datasets to quantify all inputs, which were subsequently converted into primary energy equivalents. Primary data regarding orchard establishment and annual management were collected during the 2023-2025 production seasons through field visits and interviews with a commercial nursery, local farmers, and agricultural experts from regional research institutes. The inventory characterizes the initial energy investment of the establishment phase and the annual energy flows of the operational phase, as detailed in Table 1.

Establishment Phase: This includes the primary data for nursery tree production and the materials required for the trellis system, such as concrete posts, steel anchors and tension wires. These inputs represent the "embodied energy" consumed during industrial manufacture and were annualized over the expected 20-year productive life span of the orchard.

Operational Phase: This category involves direct energy consumption, including diesel fuel for tractor-driven field operations and electricity for irrigation and self-propelled platforms. It also accounts for the indirect energy associated with the industrial synthesis of mineral fertilizers and plant protection products (fungicides, insecticides, and herbicides).

Background data for upstream processes, including machinery manufacturing and energy carriers (Italian electricity grid mix and diesel production), were obtained from the Ecoinvent v3.10, Agribalyse v3.1.1, and World Food LCA v3.5 databases.

Dataset Clarification: The primary agronomic inventory data used in this study correspond to a dataset used in a companion research project assessing broader environmental impact categories.

Input category	Unit	Tall spindle (TS)	Guyot system (GS)	%
Direct Operational Inputs				
Diesel Fuel	g kg^{-1}	6.74	6.91	+2.5%
Electricity	Wh kg^{-1}	23.12	11.67	-49.5%
Indirect/ Embodied Inputs				
Machinery	g kg^{-1}	1.21	0.40	-66.9%
Concrete posts	g kg^{-1}	11.03	12.00	+8.8%
Steel (wiring/anchors)	g kg^{-1}	1.08	1.33	+23.1%
Nursery trees	tree kg^{-1}	0.0037	0.0028	-24.3%
Fertilizers (N, P, K)	g kg^{-1}	3.84	3.91	+1.8%
Pesticides (a.i)	g kg^{-1}	0.42	0.33	-21.4%
Output				
Apple	kg	1	1	-

Note: Minor inputs, including cow manure (15.20 g kg^{-1}), irrigation system mass (2.15 g kg^{-1}), and growth regulators (0.01 g kg^{-1}), were included in the total energy calculation but omitted from the table as they did not vary between the systems.

2.4 Cumulative Energy Demand (CED) Methodology

Energy analysis was conducted using the Cumulative Energy Demand (CED) v1.12 method within SimaPro v9.6. This indicator quantifies the total primary energy embodied, including the energy used during the extraction, conversion, and disposal of raw materials. The total CED is disaggregated into six categories to provide a detailed energy source profile: Non-renewable sources: Fossil (NR-f), Nuclear (NR-n), and Biomass (NR-b), and Renewable sources: Biomass (R-b), Wind/Solar/Geothermal (R-wsg), and Water (R-wa).

3. Results and Discussion

3.1 Total Energy Demand and Energy Source Profile

Sub-categories	Tall Spindle System (TS)		Guyot System (GS)	
	MJ kg^{-1}	%	MJ kg^{-1}	%
Non-renewable, fossil (NR-f)	1.201	83.41%	0.972	87.53%
Non-renewable, nuclear (NR-n)	0.139	9.65%	0.077	6.97%
Non-renewable, biomass (NR-b)	0.00009	0.01%	0.00007	0.01%
Renewable, biomass (R-b)	0.017	1.16%	0.012	1.07%
Renewable, wind, solar, geo (R-wsg)	0.041	2.83%	0.023	2.09%
Renewable water (R-wa)	0.042	2.95%	0.026	2.33%
Total CED	**1.44**		**1.11**	

3.2 Contribution Analysis and Absolute Energy Flows

To identify the specific drivers of these energy differences, we analyzed both the percentage contributions to the primary categories (Table 3) and the absolute energy values relative to the total CED (Table 4). This dual perspective reveals not only where energy is allocated within each system, but also the magnitude of the differences between the architectural approaches.

As shown in Figure 3, the most significant energy savings in the GS were achieved by the electric harvesting platform, which decreased by 69.63% in absolute terms, from 0.35 MJ kg^{-1} in the TS to 0.11 MJ kg^{-1} in the GS. Regarding its proportional contribution (Figure 2), this input accounted for 21.62% of the fossil energy demand in TS and 8.19% in GS. Similarly, it remained the primary contributor to nuclear energy in both systems, although its share was substantially lower in the GS (31.21%) than in the TS (56.85%).

Regarding fossil energy hotspots, diesel fuel was the largest single contributor to the non-renewable fossil (NR-f) category for both architectures. In the TS, diesel fuel accounted for 31.27% of the fossil fuel demand, whereas in the GS, this share increased to 39.98%. Despite this increase in relative contribution, the absolute diesel consumption remained relatively stable, showing only a marginal increase from 0.38 MJ kg^{-1} in the TS to 0.39 MJ kg^{-1} in the GS. Chemical fertilizers constituted another major energy hotspot, with their contribution to the total fossil energy demand increasing from 18.36% in TS to 23.28% in GS. The absolute energy value for fertilizers was consistent across both systems at approximately 0.25 MJ kg^{-1}, representing a minimal variance of 1.72%.

In addition, significant changes were observed for other inputs. The reduced operation of the elevated electrical equipment resulted in a 49.60% decrease in the overall electricity consumption, from 0.199 to 0.101 MJ kg-1. Consequently, the share of electricity in renewable energy allocations decreased from 76.57% in TS to 68.20% in GS. In contrast, the energy embodied in the trellis system increased by 18.39%, from 0.04 to 0.05 MJ kg^{-1}. Additionally, the energy demand for pesticide application was reduced by 38.5%, from 0.03 MJ kg^{-1} to 0.02 MJ kg^{-1} in the GS stage.

4. Discussion

4.1.1 Tree Architecture as a Strategic Lever for Energy Efficiency

These findings suggest that orchard architecture is a primary lever for improving energy efficiency in apple cultivation. The 22.9% reduction in total Cumulative Energy Demand (CED) achieved by the Guyot system (GS) confirms that the transition from a three-dimensional to a two-dimensional canopy can decouple productivity from high primary energy intensity. The high dependency on finite, non-renewable energy sources observed in this study (exceeding 93%) aligns with the broader trends in intensive horticulture. Specifically, (Gökdoğan & Uysal, 2024) reported non-renewable inputs exceeding 90% in Turkish apple orchards, whereas (Canaj & Mehmeti, 2024) observed a similarly high fossil dependency of approximately 85% in Mediterranean apple production contexts. These comparisons highlight that although architectural redesign significantly improves efficiency, modern apple production remains deeply reliant on non-renewable energy resources.

4.1.2 Structural Trade-off: From Operational to Embodied Energy

The energy profiles of the two systems demonstrate a fundamental architectural trade-off between the capital energy invested in permanent infrastructure and the operating energy required for annual operation. In the Tall Spindle (TS) system, the vertical canopy complexity with a height of 4.0 m necessitates the use of heavy, self-propelled electric harvesting platforms for orchard management tasks. The findings indicate that the high demand for NR-n in the TS system arises primarily from the manufacturing and raw material extraction phases of the machinery rather than from operational electricity consumption alone.

In contrast, the Guyot system (GS) fundamentally shifts the energy burden by adopting an architecture-intensive model. By reducing the tree height to 3.0 m and physically constraining the canopy to a planar dimension, the system minimizes the functional requirement for a lifting platform. However, this architectural simplicity requires a significant fixed energy investment during the establishment phase. Specifically, the GS demonstrated an 18.39% increase in the absolute energy demand for the trellis system. This increase was a direct consequence of the 2.3 m row spacing, which necessitated a higher density of concrete posts and steel support wiring per hectare. This observation aligns with the engineering principle that narrow canopy architectures require more substantial support structures to maintain the vertical alignment of multiple leader shoots (Scalisi et al., 2024).

The efficiency of this trade-off was demonstrated by a 69.63% reduction in the primary energy associated with the harvesting platform and a 49.60% reduction in the overall electricity use. The Guyot system concentrates its energy requirements within the trellis infrastructure, thereby avoiding the higher recurring energy costs associated with the manufacturing and operation of complex heavy-lifting hardware. This strategic substitution indicates that, in mountain pomology, investing in the orchard's permanent physical structure offers a more energy-efficient approach than relying on mechanical solutions to address excessive canopy height.

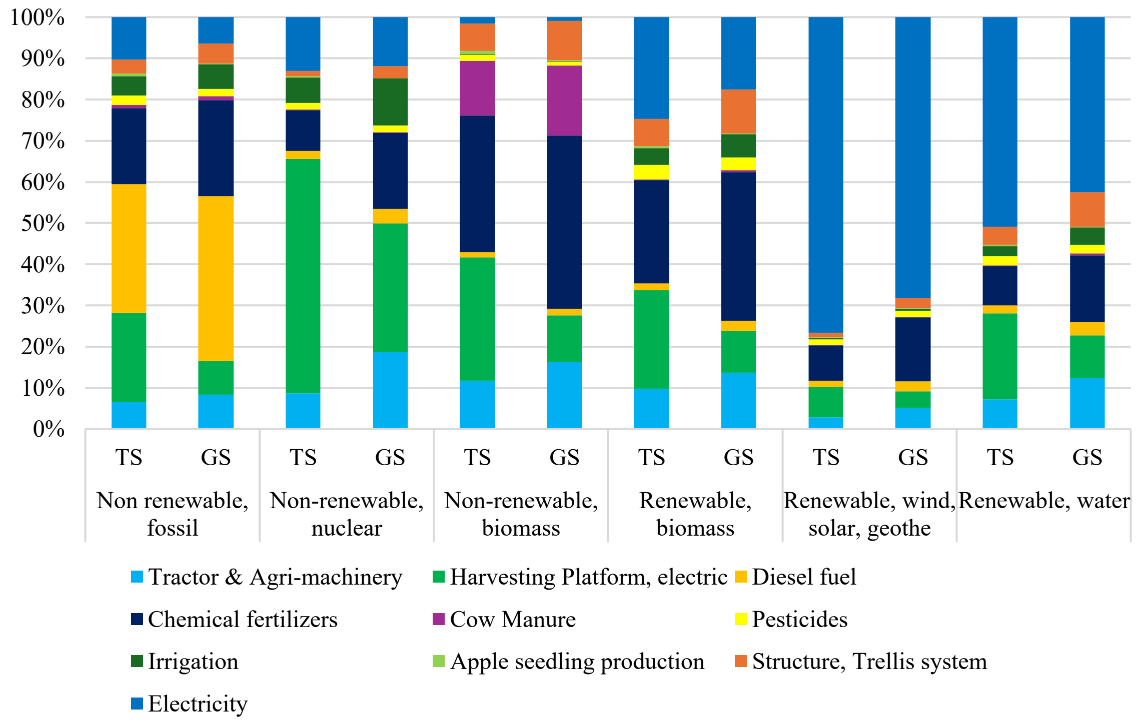

Figure 2: Percentage contribution of material inputs to primary CED categories for Tall Spindle (TS) and Guyot (GS) systems

4.1.3 Analysis of Persistent Energy Hotspots

Despite the structural trade-offs between the two systems, which highlights the inherent limitations of architectural redesign alone. Diesel fuel represents the most significant fossil energy burden for both systems, accounting for 31% to 40% of the total fossil energy demand. This finding aligns with the broader context of EU agriculture, in which on-farm diesel use accounts for approximately 31% of the total energy inputs (Paris et al., 2022). This underscores the systemic and persistent nature of diesel dependency as an energy challenge in the agricultural sector.

Similarly, chemical fertilizers remained a consistent energy hotspot across both systems, representing up to 23.28% of the total fossil energy. The minimal 1.72% difference between TS and GS indicates that the fertilizer application rates were not yet optimized for the distinct architectural requirements of each system. This confirms that the primary energy intensity of synthetic fertilizer production remains a persistent challenge in intensive horticulture, regardless of the orchard design (Majumdar & McLaren, 2024; Yan et al., 2023). These findings suggest that to achieve further energy reductions, architectural changes must be balanced with field-level technological shifts, such as precision nutrient management or the electrification of tractor-based tasks.

4.1.4 Resource Efficiency in Agrochemical and Planting Intensity

In addition to structural trade-offs, the analysis identified substantial differences in the input efficiency attributable to canopy architecture. The Guyot system demonstrated a distinct benefit in pesticide application, resulting in a 38.5% reduction in the absolute primary energy for crop protection. This improvement resulted from the narrow canopy depth of GS, which enhanced spray penetration and reduced drift compared with the more voluminous three-dimensional canopy of the TS system. These results are consistent with previous reports demonstrating that optimizing orchard architecture can substantially decrease pesticide use and spray drift (Dorigoni, 2016; Scalisi et al., 2024; Vinyes et al., 2018).

Additionally, the GS system achieved a 89.53% reduction in the absolute energy associated with seedling production. This reduction represents a significant mitigation of the energy required during the orchard establishment phase, which is directly linked to the lower planting density (2899 vs. 3906 trees ha^{-1}). By reducing the number of trees required per hectare, the system lowers the embodied energy imported from the nursery, specifically the cumulative energy spent on irrigation, fertilization, and the transport of young trees to the field. This finding indicates that the sustainability of architectural decisions influences cumulative energy savings throughout the entire orchard life cycle.

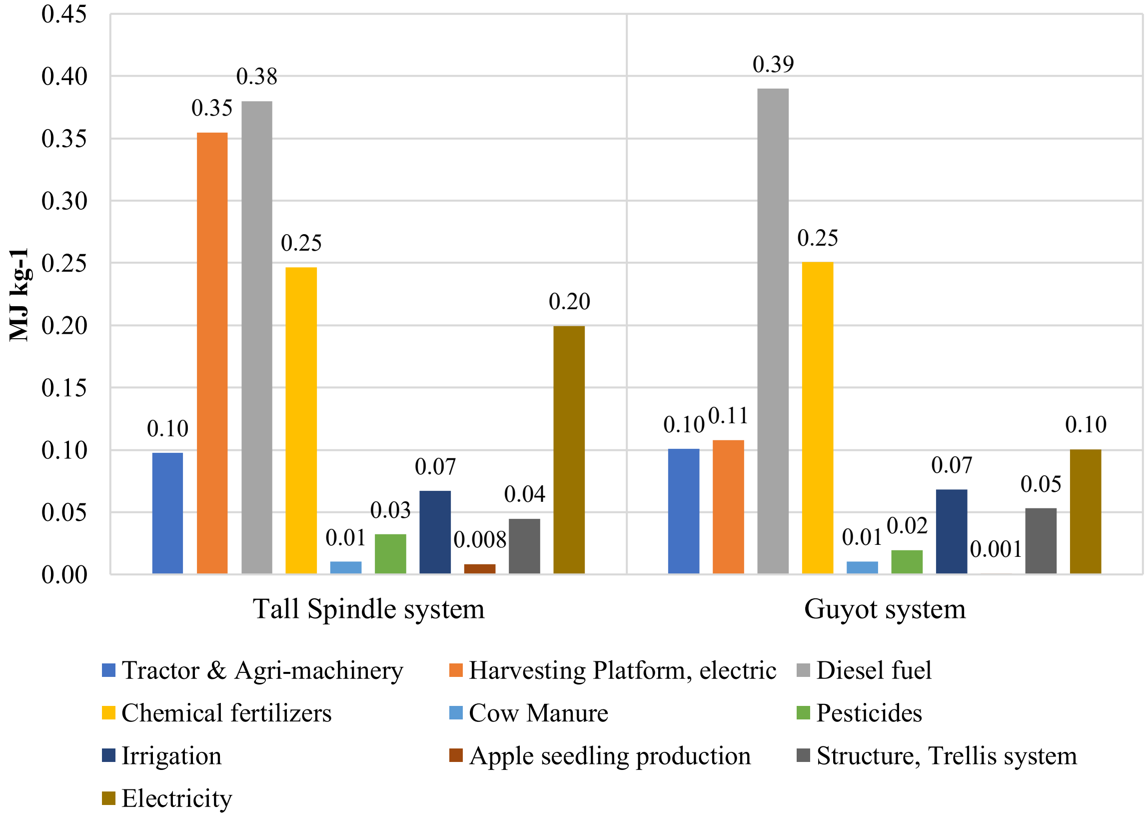

Figure 3: Absolute energy values (MJ kg^{-1}) of primary inputs for Tall Spindle (TS) and Guyot (GS) systems

5. Conclusions

This study establishes orchard architecture as the primary determinant of energy performance in mountain apple production. The Guyot training system (GS) significantly reduced the total Cumulative Energy Demand (CED) compared to the conventional Tall Spindle (TS) system, demonstrating that canopy redesign effectively optimizes resource use. This energy advantage arises from a strategic reallocation between infrastructure and operational inputs, whereas the transition to a narrow two-dimensional canopy enhances the efficiency of agrochemical application by improving spray coverage and reducing drift. Crucially, the Guyot system delivered energy savings without sacrificing yield, thereby highlighting its suitability for the sustainable intensification of perennial crops in areas with topographic constraints.

Looking ahead, several research and implementation pathways are essential to further the sustainability of mountain pomology. First, the identification of persistent energy hotspots during fertilization suggests that nutrient management remains an untapped opportunity for optimization, as current fertilization protocols have not been specifically adapted to Guyot architectures. Second, the compact dimensions of the Guyot system present a clear opportunity for machinery downsizing and technological specialization. Future studies should evaluate whether adopting lightweight or, ideally, electrified equipment could further reduce fossil fuel consumption. Moreover, the continued reliance on fossil energy underscores the need to integrate renewable sources for electrical and machinery operations.

Finally, a comprehensive multi-criteria decision analysis (MCDA) incorporating labor dynamics, economic costs, and land productivity over the complete orchard life cycle is required to provide stakeholders with a holistic framework for system selection. Ultimately, transitioning to narrow orchard systems, such as the Guyot model, offers a promising pathway toward more resource-efficient mountain agriculture. However, maximizing long-term sustainability will require the integration of architectural innovation with optimized input management, the adoption of renewable energy sources, and the development of context-specific adaptation strategies.

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Declaration of Interest Statement

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this manuscript.

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