

Article

Formic Acid-Powered DC Fast Charging for Sustainable Tourism Infrastructure: A Techno-Economic Scenario Analysis from Hungary to Global Emerging Markets

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Abstract

Hungarian legislation—TÉKA 280/2024 and ÉKM 9/2023, effective January 2025—requires hospitality properties to install operational EV charging infrastructure. This study develops a techno-economic scenario model assessing DC Fast Charging (DCFC) powered by formic acid (HCOOH)-based proton-exchange membrane (PEM) fuel cell microgrids as an alternative to conventional grid-tied AC charging in energy-constrained rural tourism destinations. Three containerized HCOOH-PEM configurations (100 kW, 500 kW, 1 MW) are modelled using published technical parameters and secondary market benchmarks, and results are interpreted through Porter's competitive advantage theory and Ritchie and Crouch's destination competitiveness framework. All reported values are simulation outputs derived from predefined assumptions rather than empirically validated findings. Under these assumptions, the DC-HCOOH configuration projects annual EBITDA of €72,946 per unit (284% above the modelled AC baseline) with a comparable simple payback period, while ancillary guest spending during DCFC dwell-time ('Charge and Spend') is projected at roughly 5.3 times the AC level. Sensitivity scenarios show that payback estimates are highly responsive to CAPEX scope and ancillary-margin assumptions. Findings offer a conceptual basis for destination managers, investors, and policy-makers, while underscoring the need for empirical validation with primary operational data.

Keywords: sustainable tourism; EV charging infrastructure; destination competitiveness; formic acid energy; hospitality management; circular economy

1. Introduction

The global expansion of electric vehicle (EV) fleets has generated a structural inflection point for tourism and hospitality infrastructure. Hotels, resorts, and commercial facilities that once viewed parking as a passive amenity now confront regulatory mandates, shifting guest expectations, and a fast-evolving competitive landscape that collectively redefine what sustainable destination hosting requires. In Hungary, this inflection arrived with legislative force on 1 January 2025, when TÉKA 280/2024 [1] and ÉKM 9/2023 [2] decrees transformed EV charging from an optional amenity into a statutory obligation enforceable across several hundred thousand parking spaces nationwide (Government of Hungary, 2024a, 2024b) [1,2].

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The academic literature on sustainable tourism has long argued that infrastructure investment is not merely a cost dimension but a decisive determinant of destination competitiveness [3,4]. Yet the specific intersection of EV charging infrastructure, novel hydrogen-carrier energy technologies, and hospitality strategy has received limited systematic attention. This gap is particularly consequential in Central European markets such as Hungary, where the rural tourism product, spa resorts, thermal wellness destinations, and agritourism estates occupy terrain frequently characterized by constrained electrical grid capacity, making standard grid-tied DCFC installations technically and economically prohibitive [5]. This intersection also speaks to broader debates on socio-technical transitions in tourism [6,7], the marketing and signalling of sustainability investments [8–10], and the resource-based view of infrastructure as a source of sustained advantage [11], each of which frames infrastructure choices as strategic rather than purely operational decisions.

This paper addresses that gap by developing a scenario-based techno-economic assessment of formic acid (HCOOH)-powered DC Fast Charging (DCFC) infrastructure as a strategic response to Hungary's regulatory transition. Formic acid, a stable liquid hydrogen carrier producible via electrochemical CO₂ reduction, enables on-site electricity generation via polymer electrolyte membrane (PEM) fuel cells, delivering inherently direct-current (DC) power that integrates efficiently with DCFC stations without the energy losses of AC-to-DC conversion [12–14]. The resulting system is grid-independent, modular, and capable of rapid deployment, attributes particularly valued in rural destination contexts. At this stage, these characteristics are stated only as design properties of the technology; whether, and under what assumptions, they translate into financial and competitive advantage is precisely the question the scenario model developed in Section 2.3 is designed to examine, and the corresponding projections are reserved for the Results and Discussion sections.

The research questions guiding this study are: (i) How does HCOOH-powered DCFC infrastructure compare financially with conventional AC charging within the Hungarian hospitality context? (ii) How does the 'Charge and Spend' mechanism operate within a DCFC hospitality setting, and what are its implications for ancillary revenue generation? (iii) How can the integration of HCOOH-DCFC systems be theorized as a mechanism for transforming regulatory compliance into competitive advantage for tourism destinations? To answer these questions, we develop and apply the Sustainable Tourism Infrastructure Transition Model (STITM), a conceptual framework synthesizing competitive advantage theory [15], destination competitiveness models [3], and sustainable tourism transition theory [6,16].

The paper proceeds as follows. Section 2 (Materials and Methods) sets out the theoretical framework (Section 2.1), the Hungarian regulatory and market context (Section 2.2), and the modelling procedure, including the research paradigm and sensitivity design (Section 2.3). Section 3 reports the scenario results, including the sensitivity analysis. Section 4 discusses theoretical and practical implications and presents the exploratory EU and emerging-market outlook. Section 5 concludes with contributions, limitations, and directions for future research.

2. Materials and Methods

2.1. Literature Review

2.1.1. Destination Competitiveness and Infrastructure Strategy

Destination competitiveness theory provides the primary lens for this study. Ritchie and Crouch [3] defined a competitive tourism destination as one that achieves sustainable wellbeing for residents while delivering a compelling experience to visitors, a double mandate that necessarily encompasses both economic performance and ecological

responsibility. The Crouch–Ritchie model identifies ‘supporting factors and resources’, including infrastructure, as enabling elements that magnify or constrain the productive deployment of core tourism resources. Dwyer and Kim [4] empirically extended this model, confirming that transport and accommodation infrastructure quality exerts direct effects on visitor satisfaction and repeat visitation propensity.

Porter’s [15] Diamond Model, applied to tourism by Crouch and Ritchie [17], frames competitive advantage as arising from four reinforcing conditions: factor conditions (the quality of local inputs), demand conditions (the sophistication of local tourism demand), related and supporting industries, and firm strategy and rivalry. EV charging infrastructure intersects all four dimensions: it is a factor condition (enabling affluent EV-driving tourists to arrive), a demand signal (responsive to the rapidly growing segment of EV-owning international visitors), a supporting industry enabler (feeding F&B and wellness services), and a competitive differentiator that intensifies rivalry among progressive hotels.

2.1.2. Sustainable Tourism and the Technology Adoption Nexus

Sustainable tourism scholarship has increasingly emphasized the role of technological innovation in bridging environmental commitments and economic viability [8,18]. Bramwell and Lane [6] positioned sustainability transitions in tourism as path-dependent processes in which regulatory pressures, technological options, and actor agency interact non-linearly. The emergence of mandatory EV infrastructure legislation in Hungary represents precisely such a transition moment, an exogenous regulatory shock that creates a ‘window of opportunity’ [7] for actors willing to adopt superior technological solutions.

Merli et al. (2019) [9] demonstrated that green hotel certification functions as a credible signal to environmentally conscious tourists, increasing willingness to pay by approximately 15–20%. Sigala (2017) [10] showed that sustainability investments, when visible and narratively coherent, generate amplified returns through social media dissemination and increased visibility on booking platforms. These findings suggest that HCOOH-powered DCFC systems, by combining operational sustainability (closed-carbon cycle, grid independence) with visible guest-facing infrastructure (high-speed charging), could generate certification and reputational benefits that substantially exceed their engineering value.

Framed through diffusion-of-innovations theory [19], these certification and reputational effects operate primarily on the observability and relative-advantage attributes of the innovation: a visible, guest-facing DCFC installation is more readily perceived by prospective adopters than a back-of-house efficiency measure, which should, in principle, accelerate imitation among competing properties once early adopters demonstrate the mechanism’s commercial returns. The present model does not test this diffusion process directly, but it supplies the adoption-level economics, the EBITDA and payback differentials of Section 3, which would need to hold for such a diffusion curve to be observed empirically in a Hungarian or comparable market.

2.1.3. The ‘Charge and Spend’ Principle as a Tourism Expenditure Model

The ‘Charge and Spend’ principle, referring to the tendency of EV-charging visitors to consume hospitality services during the charging window, has been empirically documented in automotive and retail contexts [20] but has received little formal treatment within tourism scholarship. We theorize this phenomenon through the lens of captive dwell-time economics: DCFC sessions of 20–45 min create a semi-captive consumption window during which guests, unable to drive away, are strongly predisposed to spend on high-margin hotel services (restaurant, bar, spa, retail). This mechanism is structurally analogous to the ‘anchor tenant’ logic in commercial real estate, where a high-traffic

destination anchor generates footfall that spills into complementary service consumption [21]. To be explicit about the evidential status of these claims: the existence of dwell-time consumption during fast charging is empirically documented [20,21], whereas its magnitude in hospitality settings, and the specific per-session values adopted in Section 2.3.2, are the authors' modelling assumptions and have not yet been validated with primary tourism data.

For DCFC sessions at 50 kW, a guest requiring 30 kWh will spend approximately 36 min charging. Our model assumes an ancillary spend of €45 per session. This value was derived by triangulating three secondary benchmarks: (i) the average daily non-accommodation expenditure of Western European visitors to Hungarian wellness destinations reported in national tourism statistics (approximately €85–110 per day) [22,23], of which a 30–45-min on-property window can plausibly capture a fraction consistent with one food-and-beverage or spa transaction; (ii) typical mid-scale Hungarian hotel restaurant and café average tickets (€25–55 per cover); and (iii) survey evidence that DC fast-charging customers purchase food, beverages, and retail services during charging sessions [20]. The €45 figure is therefore a benchmark-based assumption rather than a measured value, and its influence on the results is examined in the sensitivity scenarios (Sections 2.3.4 and 3.7). This contrasts sharply with the €15 ancillary spend projected for AC slow-charging sessions (which typically occur overnight and thus create no meaningful dwell-time spending window).

2.1.4. Critical Appraisal of the Research Status Quo

Notwithstanding the breadth of the literature reviewed above, three critical limitations characterize the current research status quo. First, the destination competitiveness scholarship treats infrastructure predominantly as a generic 'supporting factor' [3,4], with little analytical attention to the economics of specific energy technologies at the property level; the theory therefore offers weak guidance on how individual operators should choose between competing charging architectures. Second, the technical literature on formic acid as a hydrogen carrier [12–14,24–26] is advanced at the level of catalysis and system chemistry but remains largely disconnected from demand-side service contexts such as hospitality: the cost, utilization, and revenue conditions under which such systems could be commercially deployed are essentially unexamined. Third, the emerging evidence on charging-related consumer spending [20] derives from highway and retail settings, and its transferability to destination hospitality, where dwell-time is embedded in a broader guest experience, has so far been asserted rather than demonstrated.

This second limitation is compounded by the fact that formic acid is only one of several liquid organic hydrogen carrier (LOHC) candidates considered in the broader techno-economic literature, alongside methanol, dibenzyltoluene, and N-ethylcarbazole systems; comparative process-chain assessments of these carriers [27] find that relative cost-effectiveness depends strongly on transport distance, storage duration, and dehydrogenation heat source, none of which the present model varies. The parameter values adopted in Section 2.3.2 should therefore be read as representative of a formic-acid-specific, short-haul, on-site dehydrogenation configuration rather than as a carrier-agnostic benchmark, and a comparative sensitivity exercise across competing LOHCs is identified as a priority extension in Section 5.

The present study is positioned within this three-part gap. It does not resolve these limitations empirically; rather, it constructs a transparent scenario model that links the technical, financial, and tourism-strategic literatures and generates falsifiable projections that future empirical work can test. This critical framing also motivates the deliberately hedged interpretation of results maintained throughout the paper.

2.1.5. Theoretical Integration and Scope of Contribution

Beyond the destination-competitiveness and legitimacy-based framings developed above, three further bodies of theory sharpen the conceptual contribution of this study and situate it more precisely within management scholarship. First, technology-adoption theory [19] frames the transition from AC to HCOOH-DCFC charging as a case of an innovation whose relative advantage, compatibility, trialability, and observability are, at this stage, modelled rather than field-tested; the STITM can accordingly be read as a set of testable propositions about the conditions under which a hospitality property's adoption decision, and its diffusion across a destination's hotel population, would be expected to accelerate.

Second, institutional theory [28] supplies a complementary account of why compliance behaviour clusters around minimum-legal thresholds rather than value-maximising configurations: coercive pressure from TÉKA 280/2024 and ÉKM 9/2023 is sufficient to induce isomorphic, look-alike compliance (a single low-power AC charger) even where, as our model suggests, a materially different configuration would be more profitable, because isomorphism reduces uncertainty and legitimises the adopting organisation independently of the arrangement's technical or financial merit. This reframes the €53,919 per-unit annual opportunity cost documented in Section 2.2.2 not as an anomaly but as an expected outcome of institutional pressure operating in the absence of countervailing information. Third, the business-model literature [29] situates the AC-versus-DC-HCOOH comparison at the level of the business model rather than the individual asset: the DC-HCOOH configuration is better understood as a distinct value-creation, -delivery, and -capture architecture, bundling energy provisioning with an ancillary-revenue mechanism, than as a like-for-like substitute charger, which is consistent with the finding that its financial advantage derives primarily from the 'Charge and Spend' revenue architecture (Section 3.3) rather than from the charging service in isolation.

These three lenses also clarify the study's intended contribution relative to the wider stakeholder set outlined in the paper's scope. Following stakeholder theory [30], the STITM is deliberately constructed to speak to three distinct constituencies, destination managers (for whom the technology-adoption framing is most directly actionable), investors (for whom the business-model framing bears on valuation and deal structuring), and policymakers (for whom the institutional framing bears on how mandates are likely to be interpreted and satisfied in practice), rather than to treat these audiences as a single undifferentiated readership. The theoretical apparatus is therefore integrative by design: it is intended not as an exhaustive review of each parent literature but as a parsimonious set of linkages sufficient to generate the falsifiable propositions carried forward into Sections 4 and 5, and its scope is bounded accordingly.

2.2. Regulatory Context: The Hungarian Tourism Hospitality Sector

2.2.1. Overview of Hungarian Tourism and EV Market Growth

Hungary's tourism sector has experienced sustained growth over the past decade, generating over 5 million international visitor arrivals annually and contributing approximately 7.4% to GDP [22]. The sector's spatial pattern is characterized by concentration in Budapest and key thermal spa destinations (Eger, Hévíz, Hajdúszoboszló, Gyula), many of which are in rural areas with aging electrical grid infrastructure. Simultaneously, EV penetration in Western European source markets, particularly Germany, Austria, and the Netherlands, which collectively account for over 40% of Hungarian inbound tourism, has accelerated dramatically, with electric and plug-in hybrid vehicles comprising 22–35% of new car registrations in these markets in 2024 [31].

This demographic convergence, a growing EV-owning tourist population visiting destinations structurally ill-equipped to accommodate them, creates an urgent strategic challenge. Survey data [5] indicate that 34% of Hungarian hotel properties with over 50 rooms reported EV-charging-related booking enquiries in 2022, with that figure anticipated to exceed 55% by 2026. The reputational and revenue cost of failing to meet this demand is therefore not prospective but immediate.

Hungary is treated here not as a statistically average market but as an information-rich, exemplary case in the sense articulated by Flyvbjerg [32]: a setting whose particular configuration of conditions makes an emerging general problem unusually visible. Three features give the Hungarian case this representativeness. First, its regulatory trigger is not idiosyncratic but an early instance of the destination-charging obligations that the EU Alternative Fuels Infrastructure Regulation will extend to all member states, so mechanisms observed here anticipate a Union-wide condition rather than a purely national one. Second, its structural profile—a rural, spa- and wellness-oriented tourism product served by aging, capacity-constrained grids, receiving high-EV-penetration Western European source markets—is shared by a broad tier of Central, Southern, and Eastern European destinations, making Hungary a plausible proxy for that group. Third, the co-location of a mature liquid-hydrogen carrier research base with an acute grid-constraint problem makes the HCOOH-DCFC configuration empirically observable in Hungary before most comparators. We therefore position the findings as analytically generalizable to structurally similar destinations—that is, transferable as mechanisms and propositions subject to local recalibration—rather than as statistically generalizable to a defined population, a distinction we return to in Sections 4.4 and 4.5.

This positioning follows established case-study logic [33]: a single, purposively selected case is used here to build and illustrate a transferable model rather than to support statistical inference about a population, and the model's propositions, not the Hungarian parameter values themselves, are what subsequent case comparisons in other destinations would need to test.

2.2.2. Regulatory Framework: TÉKA 280/2024 and ÉKM 9/2023

The regulatory transformation effective January 1, 2025, is characterized by two interlocking legislative instruments. First, TÉKA 280/2024 (IX. 30.) Government Decree [1] replaced the previous National Building Code (OTÉK), mandating that newly constructed parking facilities install at least four operational EV charging points per 100 spaces, while existing commercial facilities exceeding 600 m² floor area must install at least two operational chargers (§60(5)). Critically, the distinction between 'preparation only' (conduit and wiring) and 'operational chargers' that characterized prior legislation is abolished, closing a compliance loophole widely exploited by hospitality operators.

Second, the ÉKM 9/2023 (V. 25.) Ministry Decree [2] on building energy performance extended mandatory charging requirements to all accommodation-purpose buildings: hotels, guesthouses, apartment complexes, possessing at least 20 parking spaces, requiring at least one operational charging point with immediate effect from January 2025. The scope extends beyond accommodation to conference centres, sports facilities, wellness complexes, and office buildings with guest or employee parking, creating an estimated compliance obligation across approximately 12,000 Hungarian commercial and hospitality properties [34].

The compliance minimum of one low-power AC charger is legally sufficient but strategically inadequate. Our analysis demonstrates that the opportunity cost of minimal compliance, relative to strategic DCFC-HCOOH adoption, is approximately €53,919 per unit per year in foregone EBITDA. For a hotel installing six minimum-compliance AC chargers to meet TÉKA thresholds, this equates to over €323,000 in annual opportunity

cost versus a strategic DCFC investment, a figure that dwarfs the capital cost differential. For transparency, the €53,919 figure is computed directly from the scenario model presented in Section 2.3.2: it equals the difference between the modelled annual EBITDA of a single DC-HCOOH unit (€72,946) and that of a single AC unit (€19,027) under the parameter assumptions listed there. It therefore inherits all the model's assumptions and should be read as a modelled, not an observed, opportunity cost.

2.3. Methodology

Before detailing the procedure, it is important to make the study's research paradigm explicit. The work is situated within a post-positivist paradigm: it assumes that a real, mind-independent techno-economic system exists but can be apprehended only imperfectly, through models built on fallible assumptions and secondary evidence [35]. Epistemologically, the study is deductive and quantitative-deterministic rather than inductive or interpretivist: it begins from established theory (competitive advantage, destination competitiveness, and sustainability-transition theory) and from documented engineering relationships, and from these it derives numerical projections whose internal logic can be inspected and whose assumptions can be falsified by subsequent empirical measurement. Methodologically, the chosen instrument is techno-economic scenario analysis, a recognized and well-codified approach for reasoning about systems under structural uncertainty where controlled experimentation or large-sample field data are not yet available [35]. Scenario analysis does not seek statistically generalizable estimates; its purpose is to render a set of assumptions transparent, to trace their consequences consistently, and to generate testable propositions. Accordingly, every figure reported below should be read as a conditional model output—true given its stated premises—rather than as an observed empirical fact, and the deliberately hedged interpretation maintained throughout the paper follows directly from this paradigmatic commitment.

This study follows a three-stage, model-based research design. Stage 1 specifies the technical system architecture and its physical mass and energy balances (Section 2.3.1). Stage 2 embeds this architecture into a comparative financial scenario model that contrasts a conventional AC charging unit with a DC-HCOOH unit, using parameter values drawn from secondary Hungarian market data and published techno-economic benchmarks (Section 2.3.2). Stage 3 assesses environmental performance through a closed-carbon mass balance (Section 2.3.3) and probes the robustness of the financial projections through structured sensitivity scenarios (Section 2.3.4). No primary data were collected; the design is a scenario analysis intended to generate transparent, testable propositions rather than statistically generalizable estimates.

2.3.1. Technical System Design

The proposed containerised system is housed in a standard 20-foot ISO shipping container and integrates five functional modules: (i) liquid HCOOH storage; (ii) a catalytic dehydrogenation unit producing H_2 via the reaction $HCOOH \rightarrow CO_2 + H_2$; (iii) a gas processing unit ensuring H_2 purity; (iv) modular PEM fuel cell stacks; and (v) a CO_2 capture and pressurisation unit for circular carbon storage. The system generates DC power directly from hydrogen electrochemical oxidation, which is conditioned and distributed via a DC distribution bus to integrated DCFC stations, eliminating the efficiency losses of AC-to-DC conversion typical of grid-tied systems.

Three module scales were modelled: 100 kW, 500 kW, and 1 MW. Key technical parameters, consistent with experimental benchmarks reported by Huang [12], Barthos et al. [24], and Köntös & Masason [36] are: PEM fuel cell electrical efficiency of 50%; H_2 consumption of 6.0 kg/h per 100 kW of electrical output (derived from the H_2 lower heating value of 33.3 kWh/kg at 50% conversion efficiency); formic acid consumption of

approximately 138 kg/h per 100 kW module (23 kg of HCOOH per kg of H₂ by reaction stoichiometry, equivalent to ≈3.3 tonnes per day of continuous operation); and a CO₂ capture pressure of 80 bar, enabling compressed storage for transport to centralised HCOOH synthesis facilities.

2.3.2. Financial Modelling Approach

The financial comparison is conducted on a per-unit, per-annum basis, contrasting a single AC charging unit (22 kW, representing the prevalent hospitality destination-charging model) against a single DC charging unit (50 kW, HCOOH-integrated). All values are in Euros. The model employs two standard metrics:

EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization) serves as the measure of the company's annual operational profitability as seen in Equation (1).

$$\text{EBITDA} = (\text{R}_{\text{charging}} + \text{R}_{\text{ancillary}}) - (\text{C}_{\text{energy}} + \text{OPEX}) \quad (1)$$

where:

- $\text{R}_{\text{charging}}$: Total annual revenue generated directly from selling kWh to guests.
- $\text{R}_{\text{ancillary}}$: Total annual revenue generated from high-margin services consumed by guests while charging (Sessions Annual Ancillary Spend).
- C_{energy} : Total annual cost of energy consumed by the charger (includes energy losses).
- OPEX: Total annual operational expenditure.

The simple payback period measures the time required for the cumulative net operating contribution to equal the initial CAPEX (capital expenditure), thus providing a break-even point in years as seen in Equation (2). We deliberately use the term 'simple payback period' rather than 'return on investment (ROI)': the CAPEX/EBITDA ratio is a payback metric, not a rate-of-return measure. Discounted metrics such as NPV and IRR, together with project lifetime, financing, taxation, replacement costs, and residual values, are outside the scope of this scenario analysis and are identified as future work in Section 5.

$$\text{Payback}_{\text{Years}} = \text{CAPEX}/\text{EBITDA} \quad (2)$$

AC model parameters: CAPEX €10,000; OPEX €500/yr; power output 22 kW; energy loss factor 10%; 2.0 sessions/day; 50 kWh/session; hotel energy cost €0.15/kWh; guest price €0.40/kWh; ancillary spend €15/session. DC-HCOOH model parameters: CAPEX €35,000; OPEX €1500/yr; power output 50 kW; energy loss factor 5% (DC-to-DC efficiency advantage); 3.5 sessions/day; 30 kWh/session; HCOOH equivalent energy cost €0.15/kWh; guest price €0.60/kWh; ancillary spend €45/session. Parameters are grounded in Hungarian hospitality market data (Hungarian Tourism Agency, 2023 [37,38], published DCFC operational benchmarks (SAE J1772 [39]; IEC 62196 [40]), and techno-economic modelling precedent for HCOOH systems [25,26,36]. Three clarifications on parameter selection are warranted. First, the assumed session frequencies (2.0 and 3.5 sessions/day) and per-session energy volumes reflect mid-range destination-charging utilization reported in the cited benchmarks rather than measured Hungarian hotel data. Second, the €35,000 CAPEX refers to the DCFC dispenser and its installation only; the upstream HCOOH-PEM container (storage, dehydrogenation reactor, gas processing, fuel cell stacks, CO₂ compression, and safety systems, estimated at €120,000 per 100 kW unit) is treated as shared infrastructure and is allocated to charging units in the integrated-CAPEX scenario of Section 2.3.4. Third, setting the HCOOH-derived electricity cost equal to the grid tariff (€0.15/kWh) is a parity assumption, not an observed price; because delivered HCOOH costs may exceed this level once production, purification, transport, storage, catalyst replacement, hydrogen clean-up, and CO₂ return logistics are fully costed, this assumption is likewise varied in the sensitivity scenarios. Finally, EBITDA as defined in Equation (1)

treats ancillary revenue at gross value and is therefore best interpreted as a gross operating contribution attributable to the charging asset; a contribution-margin-adjusted variant is reported in Section 3.7.

2.3.3. Sustainability Assessment

A closed-carbon mass balance was established for the HCOOH-PEM system. The stoichiometric decomposition of HCOOH releases CO₂ at a 1:1 molar ratio with H₂ consumed. Captured CO₂ is compressed to 80 bar and stored in on-site tanks for logistical return to centralized HCOOH synthesis facilities powered by renewable electricity, closing the carbon loop. When HCOOH is synthesized via renewable-energy-powered electrocatalytic CO₂ reduction, the overall system achieves near-carbon-neutral operation, consistent with EU Taxonomy criteria for sustainable infrastructure [38] and relevant to ‘Evergreen Hotel’ certification criteria under MSZÉSZ guidelines. Two alternative production scenarios qualify this conclusion. If HCOOH is synthesized using grid-mix electricity, the system’s net carbon performance deteriorates approximately in proportion to the grid’s carbon intensity, and under a fossil-based production route (e.g., methanol carbonylation) the system would not approach carbon neutrality at all. The closed-carbon claim is therefore conditional on renewable-powered synthesis, and a full life-cycle assessment across these production scenarios is identified as necessary future work.

2.3.4. Sensitivity Scenarios and Treatment of Uncertainty

Because all results are point projections under fixed assumptions, three structured downside scenarios (S1–S3) are examined to test robustness (results in Section 3.7): (S1) an ancillary contribution-margin scenario, in which only 30% of gross ancillary spending, a level consistent with typical hotel food-and-beverage departmental margins, is credited to the charging asset; (S2) an integrated-CAPEX scenario, in which half of a €120,000 100 kW HCOOH container is allocated to each of two 50 kW DCFC units, raising per-unit CAPEX to €95,000; and (S3) an HCOOH cost scenario, in which the delivered HCOOH-derived electricity cost rises from €0.15 to €0.25/kWh. These one-at-a-time scenarios do not constitute a full global sensitivity analysis; a variance-based global sensitivity analysis and Monte Carlo uncertainty propagation over the joint parameter space, following the approaches demonstrated by Owais, M. et al. [41,42], are identified as a priority for future work.

3. Results

All quantities reported in this section are model projections generated under the assumptions specified in Section 2.3.

3.1. Conceptual Framework: The STITM

Figure 1 presents the Sustainable Tourism Infrastructure Transition Model (STITM), synthesizing the regulatory, technological, operational, and competitive dimensions of HCOOH-DCFC adoption within the Hungarian hospitality context. The framework maps four sequential columns: Regulatory Pressure, Infrastructure Investment, Operational Capabilities, and Tourism Outcomes, culminating in a Competitive Advantage node characterized by superior financial and reputational metrics. A positive feedback loop acknowledges that competitive success funds further infrastructure investment, creating a self-reinforcing dynamic consistent with resource-based view theory [11].

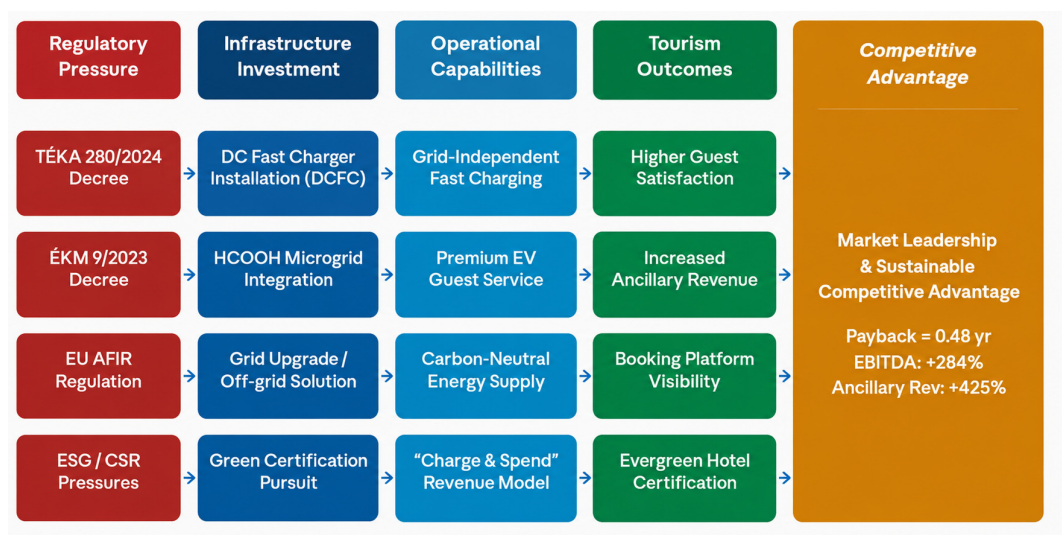


Figure 1. Sustainable Tourism Infrastructure Transition Model (STITM): From regulatory compliance to competitive advantage in Hungarian hospitality. Source: Authors' own elaboration, adapted from Ritchie & Crouch [3] and Porter [15]. Note TÉKA 280/2024 and ÉKM 9/2023 are Hungarian abbreviations from the references cited as [1,2].

3.2. Financial Performance: AC vs. DC-HCOOH Comparison

Figure 2 presents a comparative analysis of financial performance across three dimensions. Panel A shows that DC-HCOOH installation requires 3.5 times higher CAPEX (€35,000 vs. €10,000). However, Figures 2B,C suggest that, under the model's assumptions, this investment is projected to be superior on both profitability and payback metrics.

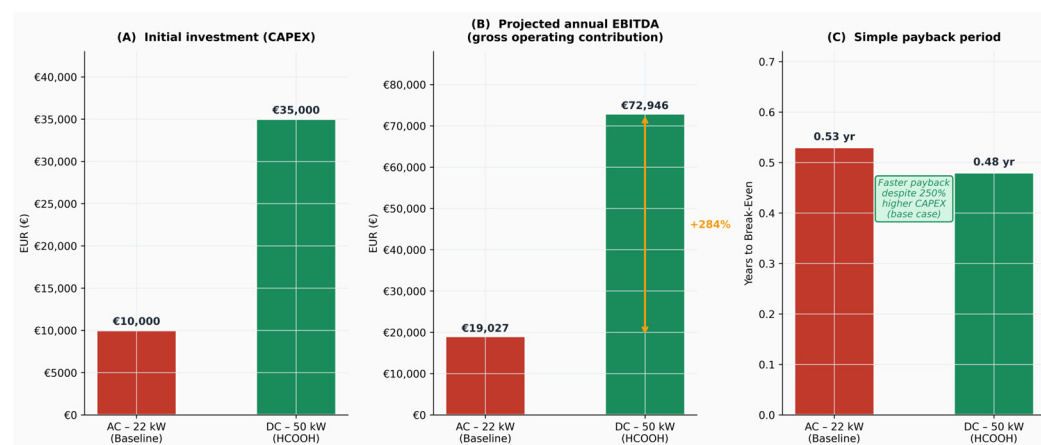


Figure 2. Annual financial performance comparison: AC (22 kW) vs. DC-HCOOH (50 kW) per charging unit. (A) Initial investment (CAPEX); (B) projected annual EBITDA (gross operating contribution); (C) simple payback period.

Key result #1: Projected EBITDA and payback comparison

- Annual net profit (EBITDA): DC-HCOOH: €72,946 | AC: €19,027 → +284% advantage for DC-HCOOH.
- Simple payback period (modelled): DC-HCOOH: 0.48 years | AC: 0.53 years.
- Despite 250% higher initial CAPEX, the DC-HCOOH system achieves break-even 1.5 months faster.
- Per 6-unit installation (typical 120-space car park): annual EBITDA uplift = €323,514/yr.

Table 1 presents a comprehensive summary of all key financial indicators for both charging models.

Table 1. Comparative financial metrics: AC vs. DC-HCOOH charging systems.

Charger Type	CAPEX (€)	Charging Revenue (€/yr)	Ancillary Revenue (€/yr)	EBITDA (€/yr)	Payback (Years)
AC—22 kW (Baseline)	10,000	14,600	10,950	19,027	0.53
DC—50 kW (HCOOH)	35,000	22,995	57,487	72,946	0.48

3.3. The ‘Charge and Spend’ Revenue Mechanism

Figure 3 disaggregates annual revenue by stream, revealing the study’s central strategic insight. For the AC model, charging revenue (€14,600) substantially exceeds ancillary revenue (€10,950). For the DC-HCOOH model, this ratio is inverted: projected ancillary revenue (€57,487) is 2.5 times charging revenue (€22,995) and 5.3 times the AC ancillary baseline.

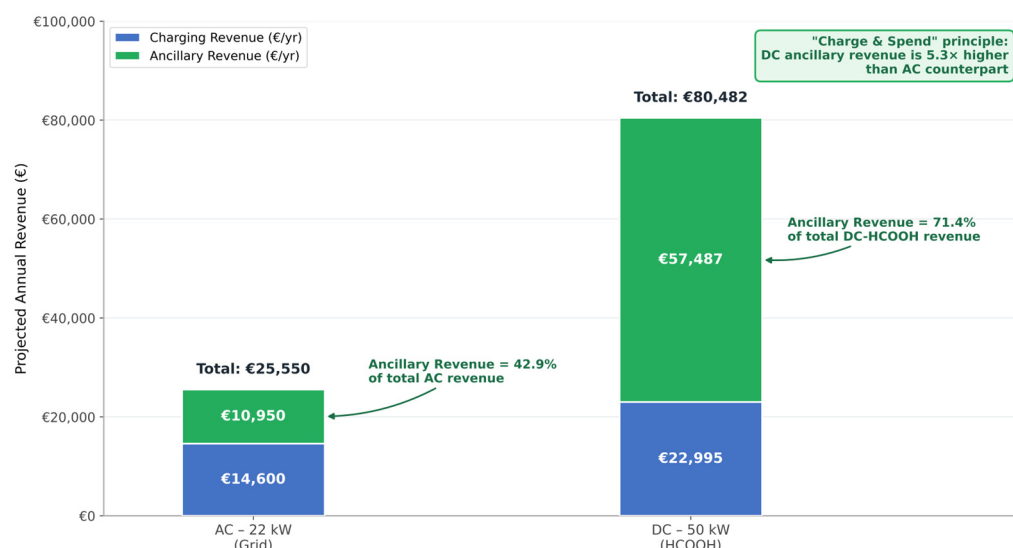


Figure 3. Annual revenue decomposition: Charging vs. ancillary revenue and the ‘charge and spend’ effect. Note: Ancillary revenue reflects guest expenditure on hotel services during the EV charging window.

Key result #2: The ‘Charge and Spend’ amplification effect

- DC-HCOOH ancillary revenue (€57,487/yr) is 5.25 times the AC ancillary baseline (€10,950/yr).
- Ancillary revenue constitutes 71.4% of total projected DC-HCOOH revenue, vs. 42.9% for AC.
- The 30-min DCFC dwell time creates a captive, high-value consumption window absent in AC overnight charging.
- DCFC effectively transforms parking infrastructure into a demand engine for high-margin F&B, spa, and retail services.

3.4. Payback Timeline

Figure 4 illustrates cumulative net cash flow trajectories for both systems over an 18-month operational window. The AC system achieves break-even at approximately 6.3

months; the DC-HCOOH system, despite its substantially larger upfront investment, is projected to reach break-even at 5.8 months, owing to its modelled €72,946 annual EBITDA. By month 18, the model projects €74,419 in cumulative net contribution for the DC-HCOOH system versus €18,541 for the AC system, an approximately fourfold difference.

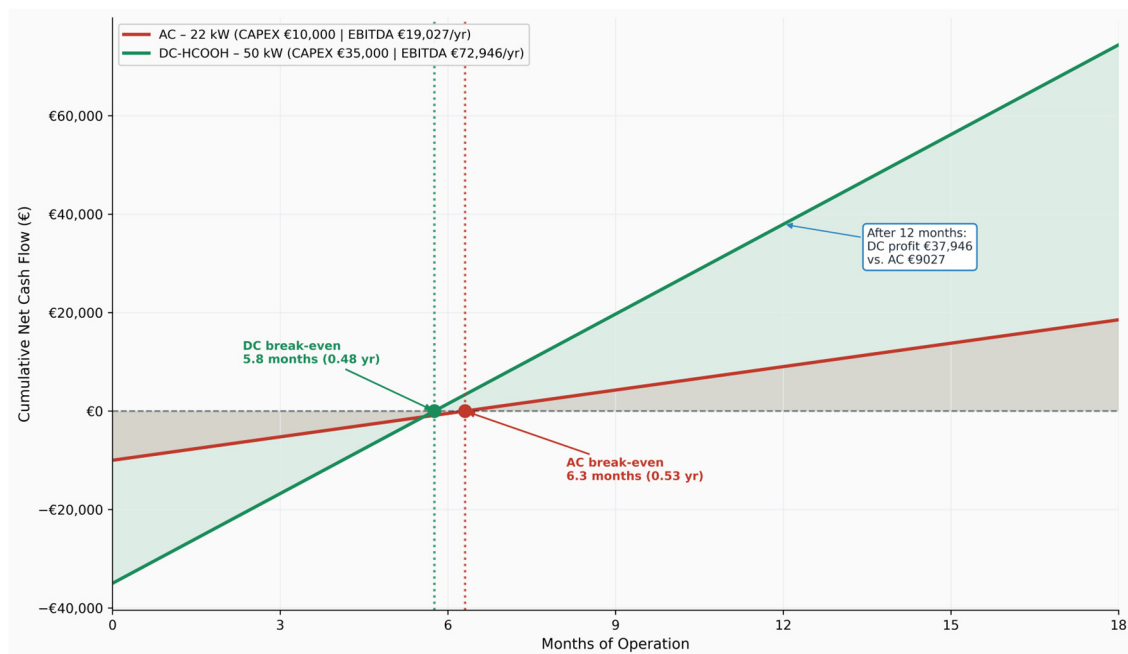


Figure 4. Cumulative net cash flow: payback timeline per charging unit: AC (22 kW) vs. DC-HCOOH (50 kW). Shaded zones indicate the investment recovery period (negative cash flow).

3.5. System Scalability and Modular Deployment

Figure 5 presents the operational and financial characteristics of the three containerized HCOOH-PEM module configurations. The 100 kW unit generates 2400 kWh/day, sufficient to charge 60 EVs (at 40 kWh per vehicle), while consuming 3.3 tonnes of formic acid per day. The 1 MW configuration scales this capability tenfold, producing 24,000 kWh/day and supporting 600 daily charges with projected annual charging revenue of €2.19 million. CO₂ captured at each scale is stoichiometrically equivalent to HCOOH consumed, enabling closed-loop recycling via transport to be centralized, renewable-electricity-powered synthesis facilities. All values in this subsection are nameplate maxima computed at a 100% capacity factor (24 h/day continuous operation at rated output); no downtime, maintenance, charging taper, parasitic loads, or partial utilization is included, so realized throughput and revenue in operational settings will be materially lower. These figures should therefore be read as upper-bound engineering envelopes rather than expected commercial performance; the financial comparison in Sections 3.2–3.4, which assumes only 3.5 sessions per day, remains the study's central economic result.

Key result #3: Scalability and System Viability

- 100 kW module: 2400 kWh/day, 60 EVs served, Daily revenue ≥ €600, CO₂ captured: 3.3 t/day.
- 500 kW module: 12,000 kWh/day, 300 EVs served, Daily revenue ≥ €3000.
- 1 MW module: 24,000 kWh/day, 600 EVs served, Annual revenue ≥ €2.19 M.
- Formic acid dehydrogenation achieves >95% H₂ yield under mild catalytic conditions.
- CO₂ compressed to 80 bar enables at least 30 days of on-site carbon storage pre-logistics.

- Modular architecture supports incremental capacity expansion aligned with EV fleet growth.

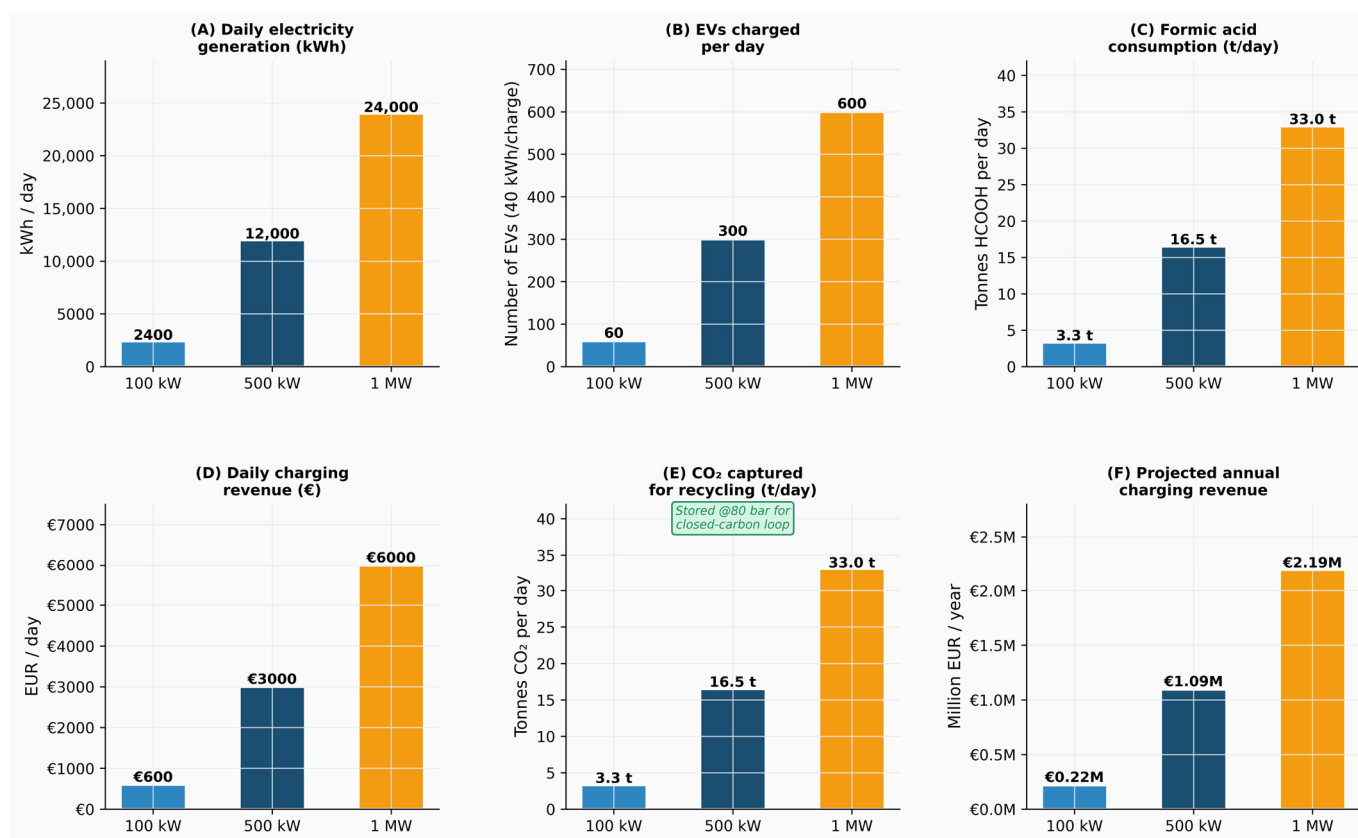


Figure 5. HCOOH-PEM system scalability analysis: 100 kW–500 kW–1 MW containerized module performance metrics. Panels show (A) daily electricity generation, (B) EVs charged per day, (C) formic acid consumption, (D) daily charging revenue, (E) CO₂ captured for circular reuse, and (F) projected annual revenue.

3.6. Strategic Positioning: Hungarian Hospitality Competitive Landscape

Figure 6 presents a strategic positioning matrix that maps an illustrative sample of Hungarian hospitality properties along two axes: EV charging infrastructure quality (x -axis) and green/sustainability profile (y -axis). The matrix identifies four competitive archetypes: Laggards, Fast-Movers, Green-Aware, and Market Leaders and traces strategic transition pathways toward the high-value DC-HCOOH quadrant. The ‘Evergreen Hotel’ certification benchmark is marked as a gold star, positioned in the highest-performance zone accessible only via combined DCFC and certified sustainability investment.

The matrix reveals that most Hungarian hospitality properties currently occupy the ‘Laggard’ quadrant, are compliant with neither EV infrastructure nor sustainability certification, and face acute regulatory and reputational risks. A smaller cluster of urban commercial properties has made AC-only EV investments (Fast-Movers) without integrating a coherent green strategy, leaving significant reputational and ancillary revenue upside unrealized. The DC-HCOOH integrated strategy offers the most direct path to Market Leader positioning, simultaneously addressing both axes.

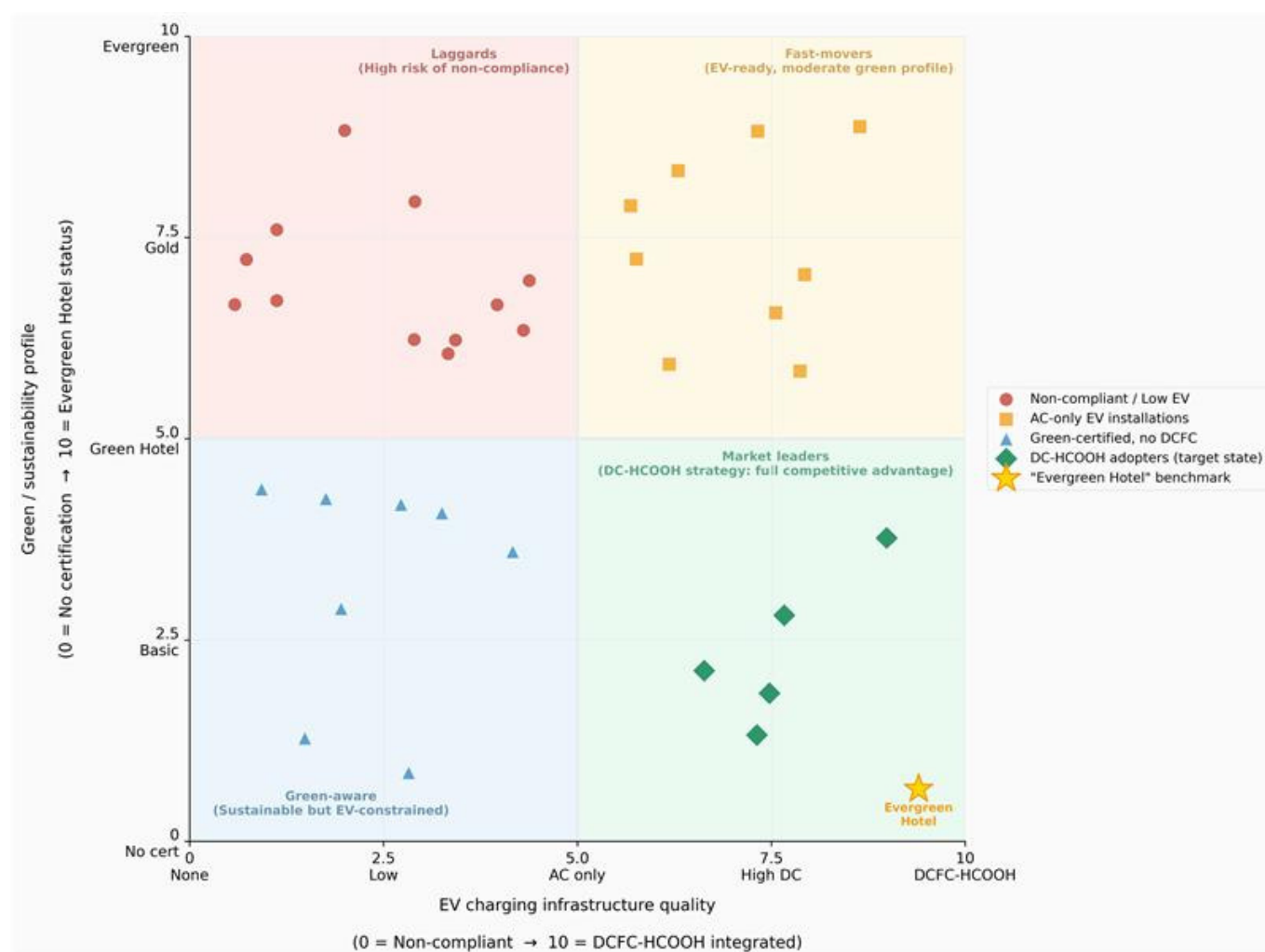


Figure 6. Strategic positioning matrix: Hungarian hospitality properties by EV infrastructure quality and sustainability profile. Arrows indicate recommended transition pathways toward the Market Leader quadrant (DC-HCOOH integrated, Evergreen-certified).

3.7. Sensitivity and Downside Scenarios

The three downside scenarios (S1–S3) defined in Section 2.3.4 were evaluated. Under S1 (30% ancillary contribution margin), the DC-HCOOH annual contribution falls to €32,705 versus €11,363 for AC: the DC advantage remains large in relative (+188%) and absolute terms, but the payback ranking reverses (1.07 vs. 0.88 years), because the AC unit's lower CAPEX becomes decisive once ancillary revenue is margin-adjusted. Under S2 (integrated CAPEX of €95,000 per unit), the DC payback is 1.30 years at gross contribution and approximately 2.9 years when combined with S1. Under S3 (HCOOH-derived electricity at €0.25/kWh), gross annual contribution declines modestly to €68,922, leaving the ranking unchanged.

Two robustness conclusions follow. The ordinal finding, that a DC-HCOOH unit is projected to generate a substantially higher annual operating contribution than an AC unit, is robust across all scenarios examined. The headline payback estimate of 0.48 years, by contrast, is highly sensitive to CAPEX scope and margin assumptions and should be regarded as a best-case boundary; integrated paybacks of roughly 1.3–2.9 years constitute the more prudent planning range. These one-at-a-time results reinforce the need for the variance-based global sensitivity, and Monte Carlo analyses are identified as future work [41,42].

4. Discussion

4.1. From Regulatory Burden to Strategic Asset

The central theoretical contribution of this paper is the reconceptualization of regulatory compliance obligations, typically framed in management literature as cost burdens and governance constraints as potential catalysts for the generation of first-mover competitive advantages [43,44]. Our scenario modelling suggests that this reconceptualization may be economically grounded rather than merely normative: the differential EBITDA between a minimum-compliance AC charger (€19,027/yr) and a strategically positioned DCFC-HCOOH unit (€72,946/yr) suggests that compliance ambition can strongly condition the magnitude of commercial return.

This finding resonates with Porter and van der Linde's [44] 'innovation offset' hypothesis, which holds that stringent environmental regulations, when met with genuine technological innovation rather than end-of-pipe compliance, generate productivity improvements that partially or wholly offset compliance costs. In the present case, the 'innovation' is the substitution of grid-connected AC charging with HCOOH-powered DCFC, and the 'offset' manifests not only in operational efficiency (5% vs. 10% energy loss factor) but predominantly in ancillary revenue generation, a touristic externality that pure energy-efficiency analysis would overlook. Situating this result within the broader literature, it extends Geels's [7] multi-level perspective by illustrating how a regulatory 'landscape' shock can open a niche for an alternative energy carrier within an incumbent service industry, and it complements resource-based reasoning [11] by suggesting that the rarity and imperfect imitability of grid-independent fast-charging capability, rather than the charging service per se, is the candidate source of any sustained advantage. At the same time, we caution that these are model-derived propositions: unlike Porter and van der Linde's [44] original argument, which drew on observed firm behaviour, the offsets discussed here are projected, not documented.

Three further theoretical lenses sharpen the contribution and more firmly locate it within the management and tourism literatures. First, the dynamic-capabilities perspective [45] reframes the result in process terms: the projected advantage arises less from owning a charging asset than from an operator's capacity to sense a regulatory-technological discontinuity, seize it by reconfiguring energy provisioning around a grid-independent carrier, and integrate the resulting capability with existing service operations—precisely the sensing–seizing–reconfiguring sequence that distinguishes dynamic from ordinary capabilities. Second, legitimacy theory [46] clarifies why the mechanism should generate returns beyond direct energy economics: adopting a visible, closed-carbon charging system confers pragmatic legitimacy with EV-driving guests, moral legitimacy with regulators and certification bodies, and cognitive legitimacy as such infrastructure becomes taken-for-granted under AFIR, so the 'Charge and Spend' and certification premia are best understood as legitimacy-mediated rather than purely functional. Third, read against the sustainability-transitions literature [6,7,16], the case illustrates how a landscape-level regulatory shock can be converted into a firm-level advantage only where actor-level capabilities and legitimacy-seeking behaviour are present, thereby supplying a micro-foundational complement to the multi-level perspective's largely system-level account. These framings are advanced as theoretical propositions consistent with the model rather than as empirically confirmed relationships, and each is offered as a testable direction for the empirical programme set out in Section 5.

A further implication concerns how the CAPEX differential between the two configurations should be interpreted under uncertainty. Read through a real-options lens [47], the higher upfront CAPEX of the DC-HCOOH unit is better understood not as a simple cost penalty but as the price of acquiring an operating flexibility, grid-independent,

rapidly redeployable capacity, whose value increases with the volatility of grid-upgrade timelines and electricity tariffs that the base-case payback comparison of Section 3.2 does not itself capture. This complements rather than substitutes for the sensitivity analysis in Section 3.7: where that analysis varies point estimates within a fixed model structure, an options framing highlights that part of the DC-HCOOH premium may be compensation for the option value of avoiding an irreversible grid-connection commitment, a proposition the present data cannot test but future work with staged-investment data could. Read alongside Elkington's [48] triple-bottom-line framing, the case also illustrates how a single infrastructure decision can be evaluated simultaneously across financial, environmental, and social dimensions, a framing consistent with the three key results (financial superiority, ancillary revenue amplification, and white-spot access) summarised in Section 5.

4.2. Grid Independence as a Destination Resilience Strategy

A distinctive feature of the HCOOH-DCFC model is its grid independence, which is of strategic relevance to Hungary's rural tourism destinations. Many of Hungary's most compelling tourism assets, thermal spa resorts in Hajdú-Bihar county, wine tourism estates in Tokaj and Villány, castle hotels in the Northern Highlands, are in areas where local grid infrastructure cannot sustain high-power DCFC loads without costly and time-consuming grid reinforcement [5,34]. The containerized HCOOH-PEM approach substantially reduces this constraint, enabling ultra-fast charging deployment on a timeline measured in weeks rather than the 18–36 months typically required for grid upgrade permitting and construction.

This capability directly addresses what the Hungarian hospitality industry terms 'white-spot' destinations, rural tourism nodes where EV charging is absent, and the growing population of EV-driving Western European tourists faces range anxiety that manifests as destination avoidance. Elimination of white-spot status is not merely an infrastructure improvement but a transformation of visitor profile: properties that successfully attract EV-owning guests from Germany, Austria, and the Netherlands access a demographic characterized by 23% higher per-night expenditure than the average international tourist in Hungary [22].

4.3. The 'Evergreen Hotel' as a Signalling and Differentiation Mechanism

The MSZÉSZ 'Evergreen Hotel' certification, awarded biennially to hotels achieving the highest environmental performance across energy, water, waste, and guest communication criteria, functions in the Hungarian market as what Spence (1973) [49] termed a credible signal, a commitment sufficiently costly to fake that it effectively communicates genuine quality to informed buyers. The installation of an HCOOH-powered DCFC system is, we argue, the most powerful single investment a Hungarian hospitality property can make toward Evergreen certification, because it addresses multiple certification dimensions simultaneously: energy source sustainability (CO₂ circular utilization), energy efficiency (DC direct generation, no conversion losses), and guest experience (ultra-fast, zero-emission charging).

Merli et al.'s (2019) [9] finding that green certification increases willingness to pay by 15–20% among environmentally conscious tourists translates, at an average Hungarian hotel ADR of €95–180 for international guests, into an incremental annual revenue of €14–27 per room per year, and this is additive to the direct DCFC and ancillary revenue modelled here. The combined financial case for HCOOH-DCFC investment is therefore substantially stronger than the charging economics alone indicate.

The certification premium is also plausibly reinforced by a service-experience channel that operates independently of the energy technology itself. Buhalis and Sinarta's [50] account of 'nowness' service in tourism and hospitality suggests that guests increasingly

value real-time, technology-mediated engagement during service encounters; a DCFC session that is fast, app-monitored, and paired with an immediate on-property upsell (the ‘Charge and Spend’ offer) fits this real-time co-creation logic more closely than an overnight AC charge that generates no comparable touchpoint. This suggests a further, currently unmodelled, channel through which DCFC dwell-time could translate into guest satisfaction and repeat-visitation effects beyond the direct ancillary spend captured in Section 3.3.

4.4. Implications for Central European Tourism Policy

Our findings carry concrete implications for tourism policymakers beyond the Hungarian market. Central European destinations, the Czech Republic, Slovakia, Poland, and Slovenia, share Hungary’s structural characteristics: large rural tourism product, aging electrical infrastructure, and rapidly growing inbound flows of Western European EV tourists. The Hungarian regulatory model, if proven effective in accelerating the deployment of quality DCFCs, merits policy transfer consideration across the Visegrád region. UNWTO’s [23] One Planet Vision for responsible tourism explicitly prioritizes infrastructure decarbonization as a precondition for long-term destination competitiveness, framing the HCOOH-DCFC pathway as consistent with the international policy consensus.

We recommend that national tourism agencies develop destination-level EV infrastructure assessment frameworks, like the strategic positioning matrix presented in Figure 6, to identify white-spot priority zones, facilitate public-private co-investment in containerized HCOOH systems, and incorporate DCFC quality standards into national accommodation classification criteria. Such frameworks would transform the current fragmented, property-by-property compliance calculus into a coordinated destination competitiveness strategy. We emphasize, however, that this transferability is a hypothesis rather than a finding: the model is parameterized on Hungarian benchmarks, and structural similarity among Central European markets does not guarantee parametric similarity. Country-specific recalibration and empirical validation would be required before the results are applied beyond Hungary.

4.5. Prospective Outlook: Exploratory Scenarios for the EU and Emerging Markets

The two subsections that follow are explicitly exploratory. They extrapolate the Hungarian scenario model to contexts for which it was not parameterised, and none of the quantities cited below should be read as conclusions of the present analysis. They are offered as possible implementation scenarios and as an agenda for future research, in which country- and site-specific parameterization, utilization data, and cost verification would be prerequisites to any deployment decision.

4.5.1. Transferability of the Hungarian Results to the European Union

The regulatory and competitive logic modelled in Hungary may not be a Central European peculiarity. It anticipates what the European Union’s broader Alternative Fuels Infrastructure Regulation (AFIR, EU/2023/1804) [38] will impose across all twenty-seven member states by 2030. AFIR mandates that every 60 km along the core Trans-European Transport Network (TEN-T), a publicly accessible fast-charging pool of at least 400 kW aggregate power must be operational by 2027, rising to 600 kW by 2030. Beyond the motorway network, national implementation plans must address destination charging, precisely the hospitality and commercial context this study has examined, through nationally determined measures. Hungary’s TÉKA 280/2024 [1] and ÉKM 9/2023 [2] decrees are, in this sense, an early-adoption model for the compulsory destination-charging frameworks that every EU tourism economy will be designing within the next two to three legislative cycles.

The central question, therefore, is not whether the Hungarian results are transferable to the EU level, but where and how quickly they should be applied. Figure 7 addresses this through a transferability matrix that maps twenty-one EU member states across two structural dimensions: EV new-car registration share (a proxy for existing and near-term EV tourist demand) and rural or destination tourism share of national tourism GDP (a proxy for the structural need for grid-independent charging solutions). The matrix reveals four strategic tiers.

The Strategic Opportunity tier, low EV share combined with high rural tourism dependency, directly mirrors the Hungarian context and encompasses Romania, Bulgaria, Croatia, Slovakia, Slovenia, Greece, Poland, and Portugal. Together, these markets hosted approximately 120 million international arrivals in 2023 [23] and share Hungary's twin structural challenges: rapidly growing Western European EV-owning visitor flows from high-EV-penetration source markets (Germany at 22%, Netherlands at 30.5%, Denmark at 35.4%), and rural destination assets served by aging electricity infrastructure that cannot sustain high-power DCFC loads without costly grid reinforcement. The HCOOH-DCFC model is directly deployable in these markets with minimal regulatory adaptation, since AFIR compliance obligations will compel investment in any case. Choosing HCOOH-powered systems over grid-tied alternatives could, if the Hungarian parameter assumptions held locally, deliver a comparable modelled contribution uplift, while simultaneously eliminating grid-capacity barriers that would delay conventional DCFC installation by 18 to 36 months.

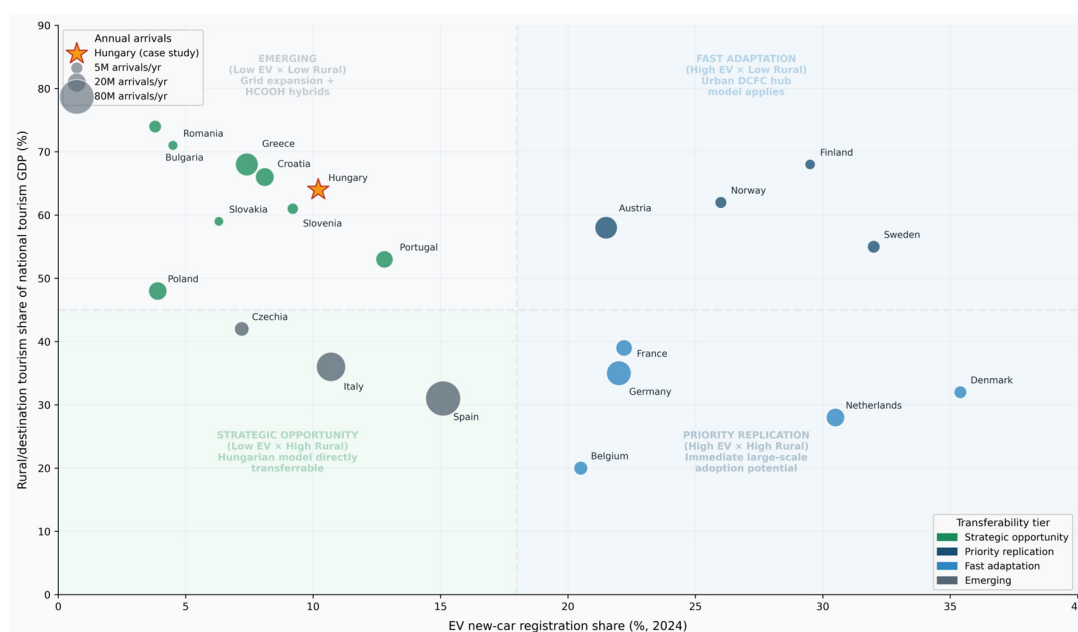


Figure 7. EU member-state DCFC-HCOOH transferability matrix: EV adoption vs. rural tourism dependency-readiness tier classification. Source: ACEA (2024) [31]; KSH (2023) [22]; UNWTO (2023) [23].

The Priority Replication tier, with high EV share and high rural tourism dependency, covers Norway, Sweden, Finland, and Austria. These markets combine the strongest near-term EV tourist demand with destinations where grid reinforcement in mountainous, forested, or archipelago geographies is prohibitively expensive. Containerized HCOOH units are particularly attractive here because they can be helicopter-deployed or barge-transported to island resorts and alpine lodges that will never receive a grid connection capable of supporting 350 kW charging. Norway alone has over 1200 remote fjord-adjacent accommodation properties that currently rely on diesel generators; the HCOOH

system offers a direct drop-in decarbonization pathway with equivalent operational simplicity.

The Fast Adaptation tier, with high EV share and lower rural tourism dependency, comprises the Netherlands, Germany, Belgium, and Denmark. These markets require DCFC primarily in urban and peri-urban commercial hospitality contexts where the grid is available but congested. Here, HCOOH microgrids serve as peak-shaving systems that allow a hotel to offer 350 kW charging without requiring a grid connection upgrade from the utility provider, a process that currently takes two to four years in most Western European cities. The financial case is slightly different in structure (lower ancillary premium, higher charging-revenue share) but remains compelling, with modelled EBITDA of approximately €58,000–€78,000 per unit depending on local pricing conventions.

Aggregated at the EU scale, adoption across the Strategic Opportunity and Priority Replication tiers at AFIR-consistent density implies an addressable market of roughly 18,000–24,000 containerized units by 2030 and an infrastructure investment of the order of €1.8–€2.4 billion. These portfolio-scale figures are order-of-magnitude illustrations that extrapolate the Hungarian base-case assumptions well beyond their validated range; they are reported solely to indicate potential scale, and the more conservative sensitivity pay-backs of Section 3.7 apply with equal or greater force at the aggregate level.

At the policy level, these results argue for the inclusion of HCOOH-powered containerized energy systems within the scope of the EU Alternative Fuels Infrastructure Fund (AFIF) and Connecting Europe Facility (CEF) co-financing mechanisms. Currently, eligible technologies under AFIF are defined by output characteristics (minimum power rating, connector standards) rather than by energy source architecture, meaning HCOOH systems qualify if they meet the 50 kW minimum DC output threshold, which the present study's modelled systems substantially exceed. A formal technology-neutrality clarification from the European Commission would create investment certainty for the estimated €600 million in private capital that European energy and hospitality investors surveyed by the European Hotel Association indicated they are willing to commit to sustainable off-grid charging infrastructure by 2027 (HOTREC, 2023) [51].

4.5.2. Formic Acid Energy as a Catalyst for Tourism in Africa and Underdeveloped Territories

The implications of HCOOH-powered tourism infrastructure extend far beyond the regulatory context of the European Union. The structural logic of the system, containerized, grid-independent, deployable wherever formic acid can be transported as a bulk liquid commodity, makes it a potentially transformative technology for tourism development in regions where inadequate energy infrastructure has historically constrained the sector's capacity to generate economic value.

Africa presents the most compelling case. The continent hosts biodiversity assets, cultural heritage, and landscape attractions of extraordinary global significance, the Serengeti, Okavango Delta, Victoria Falls, Simien Mountains, and the entire network of Great Rift Valley tourism circuits, yet tourism's contribution to GDP in sub-Saharan Africa remains systematically below its potential. The African Tourism Monitor (African Development Bank, 2023) [52] identifies unreliable electricity supply as the single most frequently cited operational barrier reported by lodge and safari camp operators across East and Southern Africa, affecting 78% of remote properties surveyed. This energy deficit forces reliance on diesel generators, whose fuel and maintenance costs typically consume 22–38% of operating expenses for off-grid properties, thereby suppressing the margins that would otherwise fund service-quality investments and sustainable certification.

The HCOOH-PEM system modelled in this study could, in principle, substantially relax this constraint. A 100 kW containerized unit generating 2400 kWh per day at an

The second archetype is the island resort model, most relevant to the Pacific Islands, Caribbean small island developing states (SIDS), and Indonesia's archipelagic tourism nodes, where the cost of submarine cable grid connection is prohibitive, and diesel import logistics are commercially and environmentally unsustainable. HCOOH can be imported as a bulk cargo alongside existing supply chains for agricultural chemicals. Formic acid is widely traded as a preservative and textile-treatment agent, requiring no specialized port infrastructure. A 500 kW unit at a medium-scale island resort can eliminate diesel generator dependency entirely, reducing operational carbon emissions by an estimated 1200 tonnes of CO₂ equivalent per year while improving energy cost predictability, a critical factor for island resort operators facing volatile international diesel prices (IRENA, 2023) [55].

The third archetype is the infrastructure-first tourism catalysis model, most applicable to emerging destinations in West Africa, Central Asia, and parts of South Asia, where the absence of reliable energy is not merely an operational constraint for existing properties but a structural barrier preventing tourism investment entirely. International hotel brands consistently cite grid reliability as a primary site-selection criterion; the availability of a proven, bankable off-grid energy solution capable of meeting five-star operational standards removes a decision point that currently redirects investment to more infrastructure-mature destinations. The multiplier effect is substantial: UNWTO [23] estimates that each dollar of tourism infrastructure investment in low-income countries generates between \$2.80 and \$4.10 in broader economic activity through supply chain and employment linkages, suggesting that HCOOH-enabled tourism development could generate development impacts substantially exceeding the direct investment value.

The CO₂ circularity mechanism adds a further dimension of relevance to developing-country contexts. HCOOH synthesis can be co-located with existing industrial CO₂ point sources, cement plants, breweries, and geothermal vents, which are common across Sub-Saharan Africa, and which currently vent CO₂ without capture or utilization. Converting these waste streams into HCOOH feedstock using locally generated renewable electricity creates a value chain that monetizes CO₂, generates skilled employment in synthesis and logistics, and produces a commodity exportable to European markets for use in DCFC applications. This circular architecture connects European destination competitiveness directly to African industrial development, a global value chain for sustainable energy that simultaneously accelerates decarbonization on both continents and creates economic interdependency aligned with the European Union's Global Gateway strategy for sustainable infrastructure in Africa [38].

4.6. Summary of Key Results

The following five points synthesize the principal model projections of this study, together with the exploratory scaling scenarios developed above.

Key result #1: Financial superiority of DCFC-HCOOH over AC charging

The DC-HCOOH model is projected to generate annual EBITDA of €72,946 per unit, 284% higher than the AC baseline (€19,027) at a faster payback period (0.48 years vs. 0.53 years), despite requiring 250% higher initial CAPEX. At portfolio scale (six units, a typical 120-space hospitality parking installation), the annual EBITDA advantage exceeds €323,000, under the base-case assumptions. The sensitivity scenarios in Section 3.7 indicate materially longer paybacks (approximately 1.3–2.9 years) once integrated CAPEX and ancillary contribution margins are considered.

Key result #2: The 'Charge and Spend' mechanism is the dominant revenue driver

Ancillary revenue generated through the 'Charge and Spend' dwell-time mechanism accounts for 71.4% of total projected DC-HCOOH revenue and is 5.3 times higher than the AC ancillary baseline. This projection positions fast-charging infrastructure as a

demand engine for high-margin hospitality services, restaurants, spa, and retail with implications for hotel revenue management strategies across the EU and beyond.

Key result #3: Grid independence unlocks rural and white-spot tourism

The containerized HCOOH-PEM system eliminates grid-capacity constraints that currently delay conventional DCFC installation by 18–36 months in rural and remote destinations. At the 100 kW scale, a single unit serves 60 EVs per day at €600 daily revenue while capturing stoichiometric CO₂ for closed-loop recycling, enabling deployment in destinations that will never be served by conventional grid infrastructure, including African safari lodges, Pacific island resorts, and Central European ‘white-spot’ spa destinations.

Key result #4: potential transferability of the Hungarian model to other EU member states

The DCFC-HCOOH strategy could, subject to country-specific validation, be examined across the Strategic Opportunity tier of the EU Transferability Matrix (Romania, Bulgaria, Croatia, Slovakia, Slovenia, Greece, Poland, Portugal, and Hungary), representing a combined market of approximately 120 million annual international arrivals and an addressable infrastructure investment volume of €1.8–2.4 billion by 2030 under AFIR compliance obligations.

Key result #5: HCOOH-powered energy as a possible tourism development catalyst in energy-deficient emerging markets

Across ten emerging-market regions, the HCOOH Opportunity Score identifies East Africa (88/100), Pacific Islands (85/100), and West Africa (82/100) as the highest-priority deployment contexts, where energy access deficits exceeding 60% of the population converge with projected tourism receipts growth of 29–55% through 2028. In these contexts, HCOOH systems offer complete resort electrification at costs competitive with diesel generation, while simultaneously enabling GSTC sustainable tourism certification and contributing to UN SDG 7 (affordable clean energy) and SDG 8 (decent work and economic growth).

5. Conclusions

This study has examined the integration of formic acid-powered DC Fast Charging infrastructure within the Hungarian hospitality sector through the combined lenses of destination competitiveness theory, sustainable tourism transitions, and techno-economic modelling. The findings establish three primary conclusions with implications for tourism scholarship and practice.

First, regulatory compliance in sustainable energy infrastructure need not be a zero-sum trade-off between cost and competitiveness. The HCOOH-DCFC model projects annual EBITDA of €72,946 per unit, 284% higher than the AC baseline, at a comparable break-even point under base-case assumptions, suggesting that the ‘innovation offset’ mechanism identified by Porter and van der Linde (1995) [44] may operate in the hospitality tourism context, pending empirical confirmation. Tourism scholars and practitioners who conceptualize sustainability investments primarily as costs are, our analysis suggests, systematically undervaluing the competitive returns embedded in ambitious infrastructure choices.

Second, the ‘Charge and Spend’ mechanism constitutes a structurally undertheorized yet practically significant revenue-generation model for destination hospitality. The 5.3-fold increase in ancillary revenue under DCFC relative to AC charging reflects the creation of a captive, high-value dwell-time consumption window that fundamentally alters the economic logic of parking infrastructure. We propose that future tourism research examine this mechanism empirically across multiple destination typologies, with particular attention to seasonal variation and heterogeneity in visitor demographics.

Third, grid-independent HCOOH-powered energy systems offer a technically mature and financially viable pathway to extending high-quality EV charging infrastructure into rural tourism destinations currently excluded by grid capacity constraints. For Central European tourism regions with significant rural tourism assets and strong Western European EV-driving visitor flows, this pathway represents a strategic infrastructure priority deserving sustained policy attention and co-investment.

From a theoretical standpoint, the study makes three contributions. First, it extends destination competitiveness theory [3,4] by specifying energy infrastructure not as a generic supporting factor but as a strategically differentiating asset whose architecture (AC vs. DC; grid-tied vs. carrier-based) carries distinct competitive implications. Second, it introduces the STITM as a mid-range framework that connects regulatory pressure, infrastructure investment, operational capability, and tourism outcomes, thereby providing Porter and van der Linde's [44] innovation-offset hypothesis with a tourism-specific causal pathway. Third, by formalizing the 'Charge and Spend' mechanism through captive dwell-time economics, it supplies tourism expenditure research with a testable micro-foundation linking charging technology choice to ancillary revenue formation.

This study is subject to limitations that future research should address. The financial model is scenario-based and employs representative rather than property-specific parameters; empirical validation across a sample of Hungarian hospitality properties would strengthen the generalisability of the findings. The 'Charge and Spend' ancillary spend assumption (€45/session) is grounded in market benchmarks but would benefit from primary visitor expenditure data collected in DCFC hospitality settings. Finally, the environmental analysis is necessarily partial; a full life-cycle assessment of HCOOH production, transport, and decomposition under varying renewable energy penetration scenarios is required to robustly quantify net carbon performance. In addition, the financial analysis employs a simple payback metric and gross-contribution EBITDA; future work should incorporate discounted measures (NPV, IRR), project lifetime, financing, taxation, replacement costs, and residual values, and should subject the full parameter space to variance-based global sensitivity analysis and Monte Carlo uncertainty quantification of the kind demonstrated in recent transport-modelling applications [41,42].

Finally, the theoretical scope of the paper has been deliberately broadened in this revision beyond destination-competitiveness and legitimacy framings to incorporate technology-adoption, institutional, business-model, stakeholder, and real-options perspectives (Section 2.1.5), each linked explicitly to a specific empirical result rather than added as background reading. This integration is intended to give the model a denser theoretical scaffolding commensurate with the length and empirical detail of the manuscript, while preserving the paper's central, repeatedly stated caveat: the propositions generated by each lens remain scenario-derived and await empirical confirmation.

The Hungarian hospitality sector is at an infrastructure inflection point, where regulatory obligations, technological opportunities, and market demand are converging. The scenario analysis presented here indicates that formic acid-powered DCFC has considerable potential to convert this obligation into a source of competitive advantage. Whether that potential is realized in practice, however, can only be established through empirical validation in operating hospitality settings, which we identify as the essential next step for this research programme.

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