Sustainable Infrastructure as a Revenue-Generating Asset: A Theory of Revenue Sufficiency

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Abstract

The social and environmental benefits as well as the investment needs of sustainable infrastructure have been well documented. Historically, green financing has been framed as a public investment problem requiring subsidies, concessional capital, or public credit support. This paper introduces revenue-sufficient infrastructure as a distinct category of sustainable infrastructure whose internally generated revenue can support financing and improve the environment without requiring a recurring public subsidy. This paper develops a theoretical framework identifying the conditions under which revenue sufficiency is achieved and applies it to publicly documented cases spanning street-furniture concessions, toll roads, congestion pricing, and green revenue bonds. This framework shows that revenue sufficiency depends less on asset type than on four institutional conditions: pricing autonomy, demand durability, contract stability, and political durability. The cases show that sustainable infrastructure can be financed through user charges, third-party revenues, or hybrid structures when those conditions protect the revenue stream across the financing horizon. They also show that financial viability is not sufficient where political durability is absent. This paper distinguishes infrastructure assets that require public subsidies from those that require a different revenue structure, thereby clarifying when private climate capital can be mobilized solely based on revenue.

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1. 1. Introduction

1.1. 1.1. Background and Research Gap

Urban infrastructure is the operating system of cities. It supports economic activity, environmental resilience, and social welfare, but it has continually operated at a financial deficit. Cities face constrained budgets, elevated capital costs, and political resistance to tax increases (OECD, 2022; Federal Reserve, 2024). The urgency of sustainable infrastructure intensifies this financing problem. Infrastructure assets that support climate, resilience, and development objectives must be deployed at a pace that conventional public finance processes may not be able to sustain (OECD, 2022; Federal Reserve, 2024). This paper defines sustainable infrastructure as urban infrastructure assets that advance climate, environmental, or UN Sustainable Development Goals (SDGs). The infrastructure asset must also contain an operating revenue component. This includes assets whose environmental contribution comes from lower-carbon mobility, water and stormwater management, utility resilience, urban service access, and more efficient use of existing infrastructure. It is commonly understood that green infrastructure creates public value. The more pressing financing question is whether some sustainable infrastructure can also generate enough operating value to close part of the infrastructure investment gap without recurring public subsidies. That question has long been obscured by the assumption that sustainable infrastructure development is dependent on grants, taxes, or public credit support. Historically, municipal finance patterns reinforce this idea. Globally, tax-generated revenue has long dominated municipal budgets, but self-financing user charges have remained a relatively small share, even as demand for resilient urban systems has increased (Hyman 1990, 675; Fuchs and United Nations University 1994).

This paper highlights current issues with investors' approach to sustainable finance and offers new terminology, including "revenue-sufficient infrastructure" and asset classification conditions. Revenue-sufficient infrastructure produces durable, enforceable, and revenue sufficient streams to secure financing without requiring a recurring public subsidy. Highway 407 ETR in Toronto illustrates the category: its long-term private concession that has expanded through toll-financed investment rather than recurring government expenditures (Ferrovial, 2024). The premise of this paper is not that all sustainable infrastructure can finance itself. It is that some sustainable infrastructure assets have been miscategorized when they do not require the use of public funds and can be directly underwritten.

This category of "revenue-sufficient infrastructure" remains undertheorized in the climate-finance literature. Most climate-finance instruments, such as concessional loans and multilateral credit enhancements, begin with the assumption that sustainable infrastructure cannot attract private capital and that public resources must bridge this gap (Global Infrastructure Hub, 2018; OECD, 2022; World Bank, 2017). Using traditional general obligation financing to build infrastructure is appropriate when an asset is not revenue sufficient, but assuming all infrastructure requires this model can lead to the overapplication of revenue-sufficient infrastructure. To prevent this incorrect categorization, the central question should shift from whether the public sector must subsidize the infrastructure assets to whether the asset's revenues are durable, enforceable, and sufficient to support repayment. The overapplication of the tax-supported borrowing model is reinforced by the recurring conflation of funding and financing. When these concepts are conflated, revenue-sufficient assets may be misclassified as subsidy-dependent and scrutinized with the same credit standards and public capital parameters used for traditional infrastructure.

No existing discussion proposes a unified theoretical framework for identifying revenue sufficiency for sustainable infrastructure. Existing literature has neglected to explore what institutional conditions make that outcome possible or how the answer should change private climate-capital deployment. The infrastructure finance literature treats the problem primarily as public capital formation (Aschauer, 1989; Gramlich, 1994). The climate finance literature often focuses on financial instruments without examining the revenue-generating ability and capacity of

the underlying assets (Flammer, 2021; Zerbib, 2019). PPP scholarship analyzes contract design and risk allocation, but it has not treated self-financing sustainable infrastructure as a distinct analytical category (Engel, Fischer & Galetovic, 2014; Grimsey & Lewis, 2004). This paper builds that bridge.

1.2. Research Question

The central research question is as follows: under what conditions can sustainable infrastructure generate revenue sufficient for self-financing, and what is the impact on private climate capital? Three supporting questions emerge within this analysis: which revenue mechanisms enable self-financing; which institutional conditions are necessary and sufficient for revenue sufficiency; and how should green bonds, PPPs, and climate-capital structures change when the underlying asset is revenue-sufficient rather than subsidy-dependent?

1.3. Theoretical Propositions

Four propositions follow from the framework and are evaluated against the case evidence in Sections 4 and 5. Proposition 1 concerns pricing autonomy. Pricing autonomy is a necessary condition for self-financing infrastructure. Proposition 2 concerns the contract horizon. Self-financing infrastructure requires contracted recurring revenue, which is consistent across the financing horizon, not just at a point in time. Proposition 3 concerns third-party revenue mechanisms. Self-financing infrastructure does not always require that the payer is the primary beneficiary. The asset's revenue stream can be partially decoupled from utilization. Proposition 4 concerns political durability. Self-financing infrastructure requires both financial viability and political durability as independent variables. An asset meeting all financial requirements can fail if political action prevents revenue collection or suppresses pricing below cost-recovery levels.

1.4. Scope and Delimitations

This paper addresses urban sustainable infrastructure assets with clear revenue streams: toll roads, congestion pricing systems, transit and street-furniture advertising concessions, and

green revenue bonds backed by utility or fare revenues. Pure public goods such as roads, flood levees, and public parks that have no feasible revenue mechanism outside of taxes fall outside the scope of this paper. Digital infrastructure assets, including EV charging networks and smart urban poles, are included only when their primary revenue mechanism is a user charge or advertising concession consistent with the taxonomy developed in Section 2. Assets whose revenue model depends primarily on data monetization are excluded because their financial structure is not analogous to the concession and user-charge models analyzed here. This analysis is theoretical, not econometric. The cases in Section 4 are illustrative calibrations against public data, not causal identification of revenue sufficiency outcomes.

1.5. Roadmap of the Paper

This paper proceeds as follows. Section 2 develops the conceptual framework: the Revenue Sufficiency Condition, the taxonomy of revenue mechanisms, and the institutional design variables that determine whether the condition holds. Section 3 situates the argument in the infrastructure finance, climate finance, and PPP literatures. Section 4 evaluates illustrative cases, including advertising concessions, toll road concessions, congestion pricing systems, green revenue bonds, and negative cases. Section 5 formalizes the Revenue Sufficiency Condition and the Self-Financing Matrix. Section 6 draws implications for green bond design, PPP contracting, and private climate capital. Section 7 concludes.

2. 2. Conceptual Framework

This section proposes the Revenue Sufficiency Condition. This framework has three components: a definition, a taxonomy of revenue mechanisms, and a set of institutional design variables that determine whether sufficiency is achieved and sustained.

2.1. Definitions and the Funding-Financing Distinction

Infrastructure finance, green bonds, and PPP scholarship often use terms such as revenue, income, profitability, funding, and financing inconsistently. The Revenue Sufficiency Condition

framework uses the traditional accounting definition of revenue: recurring gross inflows generated by the asset's own activity, excluding capital grants, tax transfers, and recurring public operating subsidies. Operating revenue is the total gross inflow generated by an asset's primary activity in a given period before costs, expenses, or obligations are deducted (IASB, 2014; FASB, 2014). In this framework, revenue is represented as “R” and includes user charges, advertising concession fees, and ancillary recurring revenues generated by the asset. Capital grants, public subsidies, and intergovernmental transfers are excluded. Without this exclusion, any infrastructure asset could appear revenue-sufficient by classifying public subsidies as revenue.

A sustainable infrastructure asset’s source of revenue can originate from user charges, third-party charges or a combination of both. User-charge revenue is commonly collected as tolls, fares, congestion charges, and utility fees. Third-party revenue includes advertising concession fees, naming rights, and ancillary commercial payments. Within this framework, each revenue source is only included as a part of R(t) when the revenue is internally generated and recurs across the financing horizon. An income-producing asset generates recurring operating cash flows from its primary function, rather than relying on capital appreciation or public service delivery (Geltner et al., 2014). Self-financing infrastructure is a subset of income-producing assets. All self-financing infrastructure assets are income-producing, but not all income-producing assets are self-financing, because income production alone does not guarantee coverage of $D(t) + O(t) + V(t)$ across the financing horizon.

Net operating income (NOI) is operating revenue minus operating and maintenance expenditure: $NOI(t) = R(t) - O(t)$. However, a clear distinction must be made between revenue sufficiency NOI. An asset with positive NOI can still fail to be self-financing if NOI is insufficient to cover debt service D(t) and volatility reserve V(t). Revenue sufficiency requires R(t) to cover D(t), O(t), and V(t) simultaneously.

Profitability is the residual surplus after operating costs, debt service, depreciation, and applicable taxes (IASB, 2003). It is not the standard used here. An asset can satisfy the Revenue Sufficiency Condition and still appear unprofitable in accounting terms because depreciation, tax

treatment, or financing structure affects reported surplus. Requiring profitability would also exclude municipal utilities and regulated concessions that are designed for cost recovery rather than accounting profit, even though they may still support investment-grade debt. The relevant hierarchy is therefore straightforward: operating revenue is the gross inflow tested by the framework; NOI measures the asset's intermediate cash-generating capacity; and profitability is the residual accounting outcome, not the condition the framework is designed to test.

It is also important to distinguish the difference between funding and financing. Funding is the ultimate source of money that covers the cost of infrastructure, including public grants, tax revenues, user fees, and operating subsidies (Beecher and Kihm, 2021; Yescombe, 2014). Financing is the mechanism that mobilizes capital upfront, including bonds, project loans, and private equity, but requires a repayment component (Yescombe, 2014; Beecher and Kihm, 2021).

The conflation of these concepts has contributed to the misclassification of revenue-sufficient assets. The unresolved question is capital structure, not subsidies.

2.2. Relationship with Existing Financing Vehicles

Sustainable infrastructure is currently financed through 5 broad approaches: public debt, blended finance, PPP structures, and capital market instruments. Each approach currently embeds an assumption about the revenue-generating capacity of the underlying asset. This framework does not replace those approaches but rather helps determine which approach is more appropriate based on infrastructure asset type.

Public debt instruments, including general obligation bonds, sovereign loans, and grant-funded transfers, are secured by the creditworthiness of the issuing government rather than the operating revenue of the asset (Yescombe, 2014; Gramlich, 1994). Historically, public debt has been the dominant vehicle for infrastructure funding because of the Public Subsidy Assumption: that sustainable infrastructure development is dependent on grants, taxes, or public credit support. In OECD countries, subnational governments account for nearly 60% of total public investment but only receive 14% of revenue from user charges, reflecting a long-standing structural preference

for tax-backed financing (OECD, 2022). The use of public debt is appropriate when the asset is not revenue sufficient, but it becomes inappropriate when applied to revenue-sufficient assets because it misallocates creditworthiness. Public debt capacity should be reserved for assets that genuinely require it. This principle also applies to blended finance.

High-risk infrastructure projects can rely on blended finance, including concessional or development capital. These funds are often offered at below-market rates because the asset's risk profile makes it unattractive to commercial capital. For revenue-sufficient assets, concessional finance may help bridge the gap between initial capital deployment and mature revenues. However, it should not become the long-term funding model because it wastes scarce public or development capital where it is not needed. Concessional and development finance should be reserved for projects with real revenue gaps: where demand is structurally insufficient, pricing is constrained, or institutional conditions cannot yet support market financing.

Beyond direct capital provision, a third group of vehicles restructures how public and private parties share the risks and returns of infrastructure delivery through contractual arrangements. PPP and concession structures introduce private capital and operational capacity into infrastructure delivery. Within PPPs, the Public Subsidy Assumption is still present, but it can vary by contract type. Availability-payment PPPs pay private operators based on asset availability rather than utilization, automatically transferring demand risk to the public sector regardless of the asset's revenue-generating capacity (Engel, Fischer, and Galetovic, 2014). This structure is appropriate when demand is genuinely uncertain, but when it is misapplied to revenue-sufficient assets, it shifts risk to the public sector unnecessarily. It also obscures whether the asset could have financed itself through properly structured revenue mechanisms.

For revenue-sufficient assets, the appropriate PPP form is the demand-risk concession. Under this structure, the private operator bears revenue risk and is compensated directly from asset-generated revenues, aligning the operator's financial interest with efficient asset utilization, limiting government financial obligations, and creating a direct incentive for cost control and service quality over the concession horizon. The choice between PPP structures is not only a

procurement decision. It reflects the asset's underlying revenue sufficiency. When an asset meets the Revenue Sufficiency Condition, a demand-risk concession PPP is more appropriate because it places repayment risk on the revenue mechanism rather than on the public sector. This distinction between purpose and repayment also applies to sustainable finance instruments.

Environmental and sustainability-labeled instruments such as green bonds, sustainability-linked bonds, climate bonds, and blue bonds are fixed-income securities issued for environmental, sustainability, or climate-related purposes (ICMA Green Bond Principles, 2021). Since the first labeled green bond issuance in 2007, the market has grown significantly but remains dominated by public-credit-backed instruments rather than pure project revenue bonds (CBI, 2023; Flammer, 2021). For revenue-sufficient assets, participating in the green bond market expands the investor pool to include ESG-mandated institutional investors, which can lead to lower issuance costs and reduced dependence on public guarantees. This combination can also make private capital deployment more scalable because repayment depends on asset-level revenues rather than limited public funds.

2.3. The Revenue Sufficiency Condition

A sustainable infrastructure asset is revenue-sufficient when its operating revenues are sufficient to cover debt service, operations and maintenance, and a volatility reserve over the full financing horizon, without recurring public operating subsidies. The standard is horizon-level coverage, not point-in-time profitability. Revenue sufficiency has two related meanings in this paper. The Revenue Sufficiency Condition is the formal rule:

$$\boldsymbol{R(t) \geq D(t) + O(t) + V(t) \; for \; all \; t \in [0, H]}.$$

where R(t) is internally generated operating revenue; D(t) is scheduled principal and interest; O(t) is operating and maintenance expenditure, including lifecycle reserves; V(t) is the volatility reserve required to maintain debt service under stress; and H is the full financing horizon. The Revenue Sufficiency Test is the practical application of that rule to a specific asset. It evaluates projected revenues, debt service, operations and maintenance costs, and volatility reserves under

base, downside, and stress cases. The Revenue Sufficiency Condition defines what must be true, and the Revenue Sufficiency Test evaluates whether it is true for a given asset.

Table 1. Revenue Sufficiency Condition — Variable Definitions and Calibration Role

Variable	Definition	Included	Analytical purpose
R(t)	Internally generated operating revenue in period t	User charges, third-party revenue, ancillary recurring revenue	Identifies the asset-controlled funding source
D(t)	Debt service in period t	Scheduled principal and interest	Tests whether capital can be serviced from asset cash flows
O(t)	Operating and maintenance expenditure in period t	Routine O&M, lifecycle maintenance, administrative cost	Prevents treating deferred maintenance as revenue sufficiency
V(t)	Volatility reserve in period t	Liquidity buffer calibrated to revenue risk	Converts cost recovery into a bondable coverage standard
H	Full financing horizon	Concession term, bond tenor, or project-finance horizon	Prevents near-term cash flow from masking later structural shortfalls

Hybrid assets may calculate V(t) as the blended volatility of combined revenue streams. When user-charge and third-party revenues are imperfectly correlated, the combined reserve requirement may be lower than the reserve required for either stream alone. Institutional risk calibration sets V(t) at the reserve required for investment-grade coverage, often expressed as DSCR of 1.25x to 1.35x (Moody's Investors Service, 2023). Where the rating-agency requirement is higher, bondability rather than solvency is the binding constraint.

The volatility reserve separates cost recovery from investment readiness. An asset that barely covers scheduled principal and interest operating and maintenance expenditures, including lifecycle reserves, has no protection against demand shocks, cost escalation, or temporary political

disruption. An asset may generate enough revenue to cover debt service and operations under normal conditions but still be too high-risk to support long-term private debt. If a modest change in cost, demand, or operations would prevent repayment, then the asset is not truly revenue sufficient. This durability is important because the purpose of the framework is to determine whether an asset can support long-term financing without recurring public subsidies. The Revenue Sufficiency Condition requires a reserve against demand or revenue volatility to keep repayment stable across the financing horizon.

This component also explains why the Revenue Sufficiency Test is not the same as DSCR. DSCR measures whether operating cash flow is sufficient to cover debt service in a given period (Moody's Investors Service, 2022). The Revenue Sufficiency Test extends DSCR by adding V(t) as an explicit obligation and by requiring the condition to hold across the full financing horizon. A DSCR test can show that an asset has enough cash flow to service debt in one period. But a Revenue Sufficiency Test asks whether that coverage can be maintained across the full financing horizon, including under stress. An asset may pass a DSCR test today and still fail revenue sufficiency if future periods expose revenue shortfalls or cost pressures.

2.4. Financing Horizon and Discounting

Infrastructure assets typically carry long financing horizons ranging from 15 to 50 years depending on asset type, capital structure, and concession terms. Because of this long time period, an asset's revenue sufficiency must be tested over the full financing horizon, not just at one point in time. Long horizons introduce two problems that point-in-time coverage analysis cannot resolve: future demand uncertainty and discount-rate distortion.

The first issue is future demand risk. Revenues in year twenty-five depend on how much people still use or pay for the asset at that time. This risk cannot be known when the asset is initially financed. For this reason, the framework tests revenue sufficiency under base, downside, and stress cases. An asset is classified as self-financing only if it still meets the Revenue Sufficiency Condition in the downside case. The downside case is defined as the 25th percentile of outcomes for comparable assets over similar financing periods, consistent with infrastructure rating

methodology (Fitch Ratings, 2021). This effect is compounded by the discount rate. A higher discount rate assigns less weight to future obligations, which can cause an asset to appear financially viable in present-value terms even when it is unable to meet its costs in specific later periods.

The Revenue Sufficiency Test addresses this limitation by imposing a temporal constraint that operates independently of the discount. Rather than evaluating financial viability through a single aggregated metric, the test requires that the asset satisfy the Revenue Sufficiency Condition in each period across the financing horizon. This periodic requirement ensures that apparent aggregate adequacy does not obscure localized shortfalls in later years, thereby providing a more structurally rigorous assessment of long-run financial sustainability.

2.5. Revenue Mechanisms

The Revenue Sufficiency Condition can be met through three payment mechanisms. User charges collect revenue from direct beneficiaries, including tolls, fares, congestion charges, and utility fees. Third-party payment collects revenue from non-users, most commonly advertisers, naming-rights buyers, or ancillary commercial tenants. Hybrid payment mechanisms combine both payment types within one asset, concession, or bond structure.

Infrastructure finance often assumes that operating revenue must come from the primary user. The Revenue Sufficiency Condition departs from existing models in three ways. First, it extends the Mohring-Harwitz self-financing theorem beyond user charges to third-party revenue mechanisms. An asset can be self-financing without charging its users. Second, it treats political durability as an institutional design variable rather than a risk factor to be priced after the fact. Third, it shifts analysis from the use of proceeds to the source of repayment. Use-of-proceeds analysis determines whether a bond is green; revenue sufficiency analysis determines whether it is bondable without public support.

Table 2. Taxonomy of Revenue Mechanisms — Comparative Summary

Mechanism	Definition	Examples	Key Variables	Risk Profile	Case Evidence
User-Charge	The primary beneficiary of the infrastructure pays a fee proportional to use or access.	Tolls, transit fares, congestion charges, stormwater utility fees	Demand elasticity; pricing autonomy; captive vs. competitive demand	Demand risk is primary. Political pricing caps are the main institutional threat to R(t).	Indiana Toll Road; 407 ETR; HCTRA; Stockholm and London congestion pricing
Third-Party	A party unrelated to the infrastructure's primary function pays for access to or association with the asset.	Advertising concessions on street furniture and transit assets; naming rights; ancillary commercial tenants	Audience scale and exclusivity; advertiser demand for urban inventory; regulatory barriers to entry	Advertising market cyclicality. Lower demand risk in captive urban contexts with regulatory exclusivity.	JCDecaux (1964–present, 80 countries)
Hybrid	An asset combining user-charge and third-party revenue streams within a single concession, bond, or operating structure.	Transit systems with fare revenue and advertising concessions; toll roads with ancillary commercial development	Revenue diversification reduces single-source risk; imperfect correlation may lower blended V(t) requirement	Dual revenue exposure creates contract complexity; blended volatility reserve required.	DC Water EIB; NY State EFC (user fees across aggregated issuers)

Notes: V(t) = volatility reserve. R(t) = operating revenue in period t. Cases referenced are developed in Section 4.

2.6. Structural Condition Variables

The four necessary variables an asset must have for R(t) to be identifiable, protected, and underwritable are pricing autonomy, demand durability, political durability and contract stability. If any variable is absent, the Revenue Sufficiency Test fails regardless of the strength of the other variables. Revenue mechanisms do not automatically produce self-financing outcomes. Four institutional design variables protect the revenue stream.

Table 3. Institutional Design Variables and Revenue Sufficiency Outcomes

Variable	Condition Type	Definition	Revenue Sufficiency Role	Failure Mode	Case Evidence
Identifiable Revenue Mechanism	Necessary	The asset must generate R(t) through a definable, recurring, and internally controlled revenue stream.	Without an identifiable mechanism, the Revenue Sufficiency Condition cannot be tested or structured.	Pure public goods have no excludable revenue stream and fall outside the framework.	Present in all nine self-financing cases; absent in British Rail (franchise subsidy model)
Pricing Autonomy	Necessary	The operator's ability to set user charges or commercial prices at cost-recovery levels without binding political constraint.	Most critical variable. Where absent, R(t) cannot reach the level required to cover D(t) + O(t) + V(t).	Regulated fare caps set R(t) below the sufficiency threshold even when demand is strong.	Full: 407 ETR. High: HCTRA, Indiana, JCDecaux. Constrained: British Rail (fail), Dulles Greenway (partial fail)
Demand Durability	Necessary	The stability and predictability of demand over the financing horizon, shaped by captivity and availability of substitutes.	Converts R(t) from a contingent stream into a bondable cash flow. Reduces V(t) and supports investment-grade ratings.	Where demand is elastic and substitutes available, pricing above cost recovery accelerates demand loss.	High: 407 ETR, HCTRA, Stockholm, DC Water. Moderate: JCDecaux (regulatory exclusivity). Low: Dulles Greenway (fail)
Contract Stability	Necessary	The durability of the concession, covenant, or operating agreement across the full financing horizon H.	Makes future R(t) underwritable. Capital markets require credible evidence the revenue mechanism will remain intact.	Short or revocable contracts prevent long-term underwriting.	Concession: 407 ETR (99 yrs), Indiana (75 yrs), JCDecaux (8–20 yrs). Bond covenants: HCTRA, DC Water, NY State EFC

Political Durability	Sufficient	The protection of the revenue mechanism from policy reversal, rate suppression, or executive cancellation.	Independently necessary even when all financial conditions hold. Reversal must impose a direct cost on the reversing actor.	Executive or legislative cancellation of a financially viable mechanism.	Protected: Stockholm (referendum), London (fiscal interdependence), JCDecaux (revenue sharing). Absent: NYC (fail)

Notes: NC = necessary condition. SC = sufficient condition. D(t) = debt service. O(t) = operating and maintenance expenditure. V(t) = volatility reserve. H = financing horizon. 'Fail' denotes cases where the condition was absent and revenue sufficiency was not achieved.

Pricing autonomy is the operator's ability to set user charges or commercial prices at cost-recovery levels without political constraints. It is especially important in user-charge models because politically capped prices can prevent R(t) from covering D(t) + O(t) + V(t), even where demand is high. Contract stability is the durability of the concession, covenant, or operating agreement across the financing horizon. The Revenue Sufficiency Condition cannot rely on a seemingly long-term but practically revocable contract.

Demand durability is the stability and predictability of demand over the financing horizon, shaped by the level of need and the availability of other substitutes. Assets with captive or legally required demand, such as a toll road serving the only practical route between two points or a stormwater utility providing a mandated service, have stronger demand durability than assets competing with free or lower-cost alternatives. Because durability is distinct from current usage, the Revenue Sufficiency Condition evaluates substitutes that could divert enough demand under downside conditions to threaten sufficiency.

Political durability is the protection of the revenue mechanism from policy reversal, rate suppression, or cancellation. Political durability must be distinct from financial viability because an asset may meet revenue coverage conditions while still failing because political action prevents revenue collection. However, pricing autonomy and political durability are partly co-determined. In the Revenue Sufficiency Condition, political risk is not merely an exogenous discount-rate

input; it is a design variable mitigated through rate covenants, statutory insulation, termination compensation, or independent regulatory authority.

Bondability is the capital-market expression of the preceding conditions rather than an independent feature. When an asset's structural and durability conditions are strong, capital markets will recognize it as underwritable.

3. 3. Literature Review

The relevant literature falls into three bodies of work: public capital formation, PPP and concession risk allocation, and climate-finance instruments. Public capital formation helps explain why infrastructure gets built, who pays, and where returns accrue and are distributed. The PPP and concession finance literature provides tools for risk allocation and contract design but has not applied those tools to sustainable infrastructure as a distinct self-financing category. Finally, the climate finance literature documents the growth of sophisticated capital-mobilization instruments, but it tends to analyze the use of proceeds rather than the source of repayment.

Each contributes an insightful context, but of them, individually or in combination, provides a unified method for determining whether a sustainable infrastructure asset is revenue sufficient. That gap is not an oversight. All three studies share the Public Subsidy Assumption. This paper does not accept that premise as universal.

Table 2b. Literature Streams and the Revenue-Sufficiency Blind Spots

Literature stream	Core contribution	Typical unit of analysis	Implicit assumption	Blind spot addressed here
Public capital formation	Aschauer (1989) and Gramlich (1994) establish infrastructure as productivity-enhancing public capital with broad, often non-	Aggregate public investment and social returns	Infrastructure generally requires public provision or subsidy because benefits spill beyond the asset owner.	Asset-level heterogeneity: some sustainable infrastructure creates internally appropriable revenue sufficient for financing.

	appropriable returns.			
PPP and concession finance	Engel, Fischer, and Galetovic (2014), Grimsey and Lewis (2004), and Guasch (2004) explain demand risk, contract design, renegotiation, and value-for-money logic.	Project contracts and risk allocation	Demand risk often justifies availability payments or public-sector risk absorption.	When protected revenues make demand-risk concessions viable without recurring public payment.
Climate finance and green bonds	Flammer (2021), Zerbib (2019), and green-bond practice explain pricing, certification, signaling, and use-of-proceeds allocation.	Financial instruments and investor behavior	Green classification is mainly tied to use of proceeds or issuer credit.	Whether the project's own revenue stream can repay capital without public credit support.

3.1. Infrastructure Finance and the Public Subsidy Assumption

The infrastructure finance literature begins from a foundational claim: infrastructure produces such broad economic benefits that private actors cannot fully appropriate; therefore, a public provision or subsidy is necessary. Aschauer (1989) links public infrastructure investment to productivity growth, and Gramlich (1994) frames infrastructure as an optimal public investment problem. Together, they establish what this paper calls the Public Subsidy Assumption: the treatment of infrastructure, as a general category, as requiring public financing because market revenue mechanisms cannot recover its costs.

The Public Subsidy Assumption is not without empirical support. In emerging markets and developing economies, government entities and state-owned enterprises accounted for approximately 83% of infrastructure investment as of 2017. In OECD countries, subnational governments account for nearly 60% of total public investment but derive only 14% of revenue from user charges. This imbalance reinforces public-credit-backed financing and suppresses

revenue-based models. In the United States, approximately 90% of public capital spending is debt-financed through tax-exempt municipal bonds, while infrastructure's share of local government expenditure has declined.

A parallel literature on infrastructure as an asset class complicates but does not overturn this assumption. Helm (2009) documents how privatized network industries created stable, regulated cash flows capable of attracting private capital. O'Neill (2013) shows institutional investors classifying infrastructure as long-duration, inflation-linked assets. While this literature primarily focuses on regulated utilities, it still fails to explain how to categorize revenue-sufficient sustainable assets from subsidy-dependent ones before the financing structure is chosen. The funding-financing conflation continues to reinforce the infrastructure investment gap. Beecher and Kihm (2021) distinguish funding, the ultimate source bearing infrastructure's cost, from financing, the mechanism that mobilizes capital against expected repayment. Although it is conceptually clear, this distinction is not consistently applied. Investment gaps are routinely treated as financing problems when, for some assets, the prior question is how to structure capital against an existing revenue stream.

3.2. Green Finance and Sustainable Investment Vehicles

Green finance has expanded from a specialist niche in 2007 into a mainstream capital-market segment. Green finance encompasses the allocation of capital toward projects and instruments that advance environmental sustainability, including renewable energy, clean transportation, and resilient infrastructure (ICMA Green Bond Principles, 2021; CBI, 2023). Flammer (2021) links green bond issuance to improved environmental performance and positive market response; Zerbib (2019) identifies a pricing effect connected to investor environmental preferences; and Tang and Zhang (2020) find positive abnormal returns around green bond announcements. These contributions establish that climate-oriented capital-market instruments are credible, not merely cosmetic.

However, the literature is centered on analyzing financial instruments. It analyzes how capital is raised and where it is directed; it does not analyze whether the underlying asset can

independently support repayment. The resulting institutional frameworks reinforce this orientation: the ICMA Green Bond Principles (2021) define eligibility by use of proceeds, and UNFCCC climate finance frameworks measure success through capital mobilized toward climate objectives rather than through asset-level revenue characteristics.

The consequence of the Public Subsidy Assumption is also observable in the market structure. The Climate Bonds Initiative estimates that revenue-backed green bonds represent less than 15% of total green bond issuance (CBI, 2023). However, there are examples such as Mexico City's 2016 municipal green bond, a $50 million issue that was oversubscribed by 250% and whose debt was serviced by transit and utility revenues without public resources. This asset is evidence that such assets do exist, but the market lacks a systematic method for identifying them.

3.3. PPP and Concession Finance

The PPP literature comes closest to addressing the self-financing question because it takes revenue structure seriously. PPP scholarship provides the tools most directly applicable to the self-financing question. Engel, Fischer, and Galetovic (2014) identify demand risk as central to PPP design. Their work distinguishes availability-payment structures, which transfer demand risk to the public sector, from demand-risk concessions, which rely on user or third-party revenue. Grimsey and Lewis (2004) emphasize risk allocation and value-for-money logic, and Guasch (2004) documents the prevalence of renegotiation under political pressure. An earlier precedent comes from transportation economics: Mohring and Harwitz (1962) demonstrate that road infrastructure can be self-financed through toll-based cost recovery under specific demand conditions.

3.4. The Gap This Theory Fills

The same gap appears across all three literature categories. Each recognizes that infrastructure can generate revenue, attract private capital, or produce public benefits, but none places revenue origination at the center of the analysis. None asks a prior question that is essential

to infrastructure finance: which sustainable infrastructure assets can generate enough operating revenue to support capital financing without recurring public subsidies, and which cannot?

This omission matters because the private market and finance literature are moving in different directions. Private infrastructure assets under management have grown from $500 billion in 2016 to more than $1.5 trillion by 2025, reflecting growing investor demand for long-duration, inflation-linked cash flows. At the same time, over 80% of infrastructure is financed through public resources (OECD, 2022). Private capital is increasingly seeking infrastructure-like assets, but many sustainable infrastructure projects are still evaluated and structured as if they belong only on public balance sheets. The missing step is a method for distinguishing assets that require public funding from assets that can support private or project-level financing through their own operating revenues.

This paper fills that method through the Revenue Sufficiency Condition by outlining the conditions under which sustainable infrastructure generates revenue sufficient to support capital financing without recurring public subsidies. It identifies the mechanisms through which this occurs and the institutional variables that determine whether the condition holds. The infrastructure investment gap is not primarily a shortage-of-capital problem. It is a structuring and recognition problem: assets capable of financing themselves are not being identified, organized, or presented to capital markets as such. This diagnosis requires a different starting point. Rather than assuming that infrastructure requires a recurring subsidy, researchers and developers should first determine whether the asset can meet a Revenue Sufficiency Condition and, if so, structure financing around the revenues the asset itself can sustain.

4. 4. Case Studies: Evidence of the Affirmative

This section highlights four illustrative cases to calibrate the Revenue Sufficiency Framework against public financial, regulatory, and operational evidence. These cases were selected for variation across revenue mechanisms and institutional protection, not for causal identification. Each case is evaluated against the same variables: revenue mechanism, pricing

autonomy, contract stability, demand durability, political durability, and ability to satisfy the Revenue Sufficiency Condition.

The cases span six decades of operational data, four countries, three revenue mechanism types, and assets ranging from street-furniture concessions to green infrastructure bonds. Case selection follows the logic of theoretical replication (Yin, 2018): varied institutional and operational settings are used to test the same analytical question.

The cases are not causal evidence. Infrastructure financing arrangements of this scale do not permit random assignment or clean natural experiments. They are used as calibration: evidence that the conditions specified by the framework are present in demonstrated self-financing cases and absent in failure cases. Each case follows a descriptive structure: context, data sources, analysis against framework variables, and findings (Eisenhardt, 1989; Yin, 2018).

4.1. Case A: JCDecaux and the Third-Party Revenue Model

Research context and background

JCDecaux, founded in Lyon in 1964 by Jean-Claude Decaux, is the longest-running and most widely replicated example of the third-party revenue model applied to sustainable urban infrastructure (JCDecaux, 2024). In its initial Lyon experiment, forty bus shelters were installed at no cost to the municipality, with the operator recovering installation, operating, and maintenance costs through exclusive advertising rights on the shelters (JCDecaux, 2003). By 2023, JCDecaux operated in 80 countries and 3,895 cities, generating €3.57 billion in consolidated revenue through the design, installation, operation, and maintenance of bus shelters, self-cleaning public toilets, cycle-hire schemes, and urban furniture systems.

The case is important to review because it reaches a self-financing outcome through a revenue logic different from the Mohring-Harwitz user-charge model. It tests whether a sustainable urban infrastructure asset can be revenue-sufficient when the primary user does not pay directly. It also tests whether locational scarcity, municipal contract rights, and advertising demand can create a durable revenue stream capable of supporting capital and operating obligations. For this case, V(t) is calibrated to advertising-cycle volatility and minimum municipal payment

obligations. The pandemic revenue contraction is therefore treated as a stress event, not as evidence of structural failure.

Table 4. JCDecaux Financial Summary — Revenue and Public Redistribution

Metric	2003 (Benchmark)	2019	2020	2021	2022	2023
Countries served	43	80	80	80	80	80
Cities served	3,500	3,895	3,895	3,895	3,895	3,895
Group revenue	n.r.	€3.89B	€2.31B	€2.73B	€3.32B	€3.57B
Public operating subsidy received	€0	€0	€0	€0	€0	€0
Estimated public redistribution	n.r.	≈€1.95B	≈€1.16B	1. ≈€1.37B	≈€1.66B	≈€1.79B
Primary financial logic	Organic growth	Revenue sufficiency	Revenue sufficiency	Revenue sufficiency	Revenue sufficiency	Revenue sufficiency

Sources: JCDecaux 2003 Document de Référence; JCDecaux Annual Reports 2019 to 2023; JCDecaux Socioeconomic Footprint Study (Utopies and Ernst & Young, 2024); City of Chicago Coordinated Street Furniture Program Agreement (2002). "n.r." = not separately reported in the 2003 reference document. Public redistribution estimated at fifty percent of group revenue per the audited Footprint Study methodology.

4.2. Analysis Against Framework Variables

Pricing autonomy is high, with subsector variation. In Street Furniture, advertising rates are negotiated with brand clients in competitive markets, with no municipal cap on pricing (JCDecaux, 2024). Transport concessions sometimes require host-authority approval (JCDecaux, 2023). The revenue contraction to €2.31 billion in 2020 and recovery to €3.57 billion by 2023 show both advertising-market volatility and the self-correction capacity enabled by market pricing.

Contract length and stability are high. Standard concession terms run eight to twenty years, with major-city contracts typically in the twelve-to-fifteen-year range; Chicago's 2002 Coordinated Street Furniture Program Agreement specified an initial 10.5-year term (JCDecaux, 2023; City of Chicago, 2002). In 2003, JCDecaux funded capital expenditure from operating cash flow generated by existing concessions, demonstrating the value of contracted forward revenue visibility (JCDecaux, 2003).

Demand durability is high, but the reason requires precision. JCDecaux is sometimes described as a media asset exposed to digital substitution. The concession is better understood as an institutionally protected, land-like position whose value derives from regulatory exclusivity, not merely from advertiser preference for outdoor media.

Three mechanisms create this moat. First, urban jurisdictions cap the number of permitted outdoor advertising faces through zoning and aesthetic regulation (Wilson and Till, 2011; Cronin, 2010). Second, concession contracts grant exclusive rights to regulated municipal advertising inventory, limiting competitive entry (City of Chicago, 2002). Third, physical assets occupy nonreproducible locations. Digital channels compete for advertiser budgets, but they cannot replicate regulated access to high dwell time urban positions. The 2020-2023 recovery occurred despite continued growth in digital advertising, supporting the view that scarcity and exclusivity protect the concession inventory (JCDecaux, 2024).

Political durability is also high because the revenue-sharing structure gives cities a financial reason to protect the arrangement. Boston documented USD 36.6 million in concession receipts at zero public capital or operating cost (City of Boston, 2023). Across the group, approximately 50 percent of revenue, roughly €1.79 billion in 2023, is redistributed to public partners (Utopies and Ernst & Young, 2024). Termination would impose a measurable cost on municipal partners through foregone receipts.

Risk allocation is private. Under Article 6.1 of the Chicago Agreement, the contractor's obligation to pay city fees is independent of advertising revenues, the city receives guaranteed minimum payments, and public capital outlay is identified as USD 0.00 (City of Chicago, 2002).

The operator bears advertising demand risk, while geographic diversification across 3,895 cities and eighty countries provides portfolio hedging unavailable to single-city operators (JCDecaux, 2024).

The 2020 stress event calibrates V(t). Revenue fell by approximately 40%, from €3.89 billion to €2.31 billion, comparable to severe stress scenarios used in municipal bond analysis (Beecher, 2021; Moody's Investors Service, 2023). Operations, maintenance, and municipal payments continued without public subsidies, and revenue was recovered by 2023 (JCDecaux, 2024; Yescombe, 2014).

The model also captures locational rent. High dwell-time pedestrian and transit corridors generate scarce urban attention. Without a coordinated concession, that rent would be privately fragmented, dissipated through uncoordinated installation, or lost entirely. The concession captures a contractually specified share and redistributes it to the public sector (Utopies and Ernst & Young, 2024).

The JCDecaux model is not universally replicable. It requires sufficient footfall, advertising market depth, long-horizon concession authority, and municipal capacity to enforce contracts. These conditions hold in dense urban markets with stable procurement systems but not in low-density geographies, weak enforcement environments, or jurisdictions unable to support long-term concessions. Section 5.5 develops the failure boundary.

4.3. Case B: Toll Roads and the User-Charge Model at Scale

4.4. Research Context and Background

Case B examines three toll road examples spanning the institutional range of the user-charge mechanism: the Indiana Toll Road, 407 ETR in Toronto, and the Harris County Toll Road Authority (HCTRA). Together, they show that user-charge self-financing can occur under private concession, privatized facility, and public-authority structures when the institutional variables are properly configured (Engel, Fischer, & Galetovic, 2014).

The Indiana Toll Road is analytically important because its $3.8 billion 2006 concession value is a market signal (Indiana Finance Authority, 2006). Investors underwriting a 75-year concession were effectively concluding that toll revenues would cover debt service, operating costs, and equity return over the financing horizon. No public subsidy was included in the concession terms.

The 407 Express Toll Route has operated as a privately owned toll road since its 1999 privatization for CAD $3.1 billion and runs under a concession extending to 2098 (407 ETR, 2024). HCTRA provides the public-authority comparison: its bonds are backed solely by toll revenues, are rated Aa3 by Moody's, and have not required general fund support for debt service or operations (HCTRA, 2023; Moody's, 2023).

Criterion	Indiana Toll Road	407 ETR (Toronto)	Harris County HCTRA
Revenue Mechanism	User charge (toll)	User charge (toll)	User charge (toll)
Concession or Horizon	75 years (2006 lease)	99 years (privatized 1999)	Revenue bonds; 30-year maturities
Pricing Autonomy	HIGH (limited regulatory cap)	FULL (private operator)	HIGH (HCTRA board sets tolls)

4.5. Analysis Against Framework Variables

Pricing autonomy ranges from high to full. 407 ETR is the upper bound: the private operator sets tolls without a statutory rate cap (407 ETR, 2024). The HCTRA sets rates through its board within a public accountability structure (HCTRA, 2023). Indiana permitted CPI-linked increases and specified above-CPI adjustments (Indiana Finance Authority, 2006). In each case, pricing autonomy was sufficient to preserve coverage.

Contract stability is high across all three. 407 ETR's 99-year term and Indiana's 75-year lease provide long revenue visibility. HCTRA achieves similar certainty through bond covenants

requiring toll rates sufficient to cover 1.25x debt service (HCTRA, 2023). Each structure gives capital markets a credible basis for underwriting future revenues (Yescombe, 2014).

Demand durability is high because each asset serves a limited-access corridor with constrained substitutes. The Indiana Toll Road is the primary I-90 corridor from Chicago to Ohio; 407 ETR crosses Metropolitan Toronto as a premium express route; and HCTRA serves suburban Houston growth corridors with constrained parallel capacity (FHWA, 2023). Captive demand converts toll revenue from a contingent stream into bondable cash flow (Engel et al., 2014).

Political durability is protected through provisions that make interference costly. 407 ETR includes damages provisions for government interference with pricing; HCTRA bond covenants legally protect rate-setting; and Indiana includes force majeure and change-in-law provisions that shift political interference costs to the public sector (407 ETR, 2024; HCTRA, 2023; Indiana Finance Authority, 2006).

4.6. Key Findings

Case B supports three findings. User-charge self-financing is strongest when pricing autonomy and demand durability coincide. Long concession or bond horizons make future revenue underwritable. The relevant distinction is not public versus private ownership but whether the revenue stream is protected enough to support D(t), O(t), and V(t) across H.

Table 5. Toll Road Case Studies: Revenue, Contract Structure, and Bond Coverage Data

Criterion	Indiana Toll Road	407 ETR (Toronto)	Harris County HCTRA
Revenue Mechanism	User charge (toll)	User charge (toll)	User charge (toll)
Concession or Horizon	75 years (2006 lease)	99 years (privatized 1999)	Revenue bonds; 30-year maturities

Criterion	Indiana Toll Road	407 ETR (Toronto)	Harris County HCTRA
Pricing Autonomy	HIGH (limited regulatory cap)	FULL (private operator)	HIGH (HCTRA board sets tolls)
Concession or Bond Value	$3.8B (2006 transaction)	CAD $3.1B annual revenue (2023)	Investment-grade (Moody's Aa3)
Public Operating Subsidy	None since 2006 lease	None since 1999	None; bonds sole recourse
Demand Durability	HIGH; limited-access corridor	HIGH; captive Metro Toronto	HIGH; Houston growth market

Sources: FHWA Toll Facilities Annual Data; Indiana Finance Authority concession documentation; Harris County Toll Road Authority Annual Financial Reports and MSRB and EMMA bond documents; 407 ETR Annual Reports. All data is publicly available.

4.7. Case C: Congestion Pricing, Revenue Sufficiency, and Political Risk

4.8. Research Context and Background

Case C examines Stockholm, London, and New York City. The three congestion-pricing programs hold projected financial viability relatively constant while varying sharply in political durability. Stockholm and London are operationally self-sustaining with decade-plus revenue records. New York was projected to generate more than $1 billion annually, had cleared required approvals, and was suspended by executive action before collecting a single toll (MTA, 2024). The comparison tests P4.

Stockholm introduced congestion pricing as a 2006 trial, confirmed it by referendum, and has operated continuously since (Eliasson, 2014; Swedish Transport Agency, 2023). Annual net

revenues exceed SEK 900 million, and the program has expanded twice. Nearly two decades of operation provide strong evidence of political durability.

London introduced its charge in 2003 and has generated more than £1.5 billion in cumulative net revenues for Transport for London (Leape, 2006; Transport for London, 2023). The zone has expanded through the Ultra Low Emission Zone, and durability across mayoral administrations provides a demanding test of cross-cycle resilience.

New York City received Federal Highway Administration environmental clearance and MTA Board authorization under the 2019 Traffic Mobility Act (MTA, 2024). Projected revenues exceeded $1 billion annually, enough to support $15 billion in MTA capital bonds. Governor Hochul announced an indefinite pause in June 2024 after federal review was complete but before toll collection began.

4.9. Analysis Against Framework Variables

Stockholm and London score high across the institutional variables. Pricing autonomy is preserved through statutory frameworks in Stockholm and Transport for London's operational authority in London. Contract stability is provided by legislation rather than concession contracts. Demand durability is high because central-city destinations create captive demand conditions similar to limited-access toll roads (Eliasson, 2014; Leape, 2006). Political durability is confirmed by a referendum in Stockholm and cross-administration continuation in London.

New York also scored high on pricing autonomy, demand durability, and contract stability. The MTA had statutory authority to set rates, the Manhattan Central Business District created captive destination demand, and the Traffic Mobility Act provided legislative foundation. The revenue model was credible enough to support USD 15 billion in bonds (Metropolitan Transportation Authority, 2024). Political durability was absent. A single executive decision suspended the program before revenue collection, so the Revenue Sufficiency Condition was never tested in operation.

The NYC case is decisive for P4 because all financially relevant conditions were present, while political durability was absent. Indiana and 407 ETR protect political durability through contractual penalties for interference. Stockholm protects it through referendum legitimacy. London protects it through fiscal interdependence because suspension would impair services funded by the charge. In each successful case, reversal imposes a direct cost on the political actor. In New York, no equivalent cost existed.

4.10. Key Findings

Case C isolates P4. Political durability is not reducible to demand, pricing, or projected coverage. It determines whether projected revenues can materialize. Congestion-pricing revenues can satisfy the framework where statutory and political protections hold; political interruption can destroy revenue sufficiency even when the financial model is otherwise sound.

4.11. Case D: Green Revenue Bonds and Self-Financing into Capital Markets

4.12. Research context and background

Case D examines three cases where user-fee revenues become bondable cash flows supporting green bond issuance without public subsidies: the DC Water Environmental Impact Bond, the New York State Environmental Facilities Corporation, and the Philadelphia Water Department. DC Water's 2016 Environmental Impact Bond financed green stormwater infrastructure and tied investor returns to measured runoff reduction (DC Water, 2016; Quantified Ventures, 2017). NY State EFC represents the mature model: AAA-rated water and sewer revenue bonds aggregated across the state with an unbroken debt-service history (New York State Environmental Facilities Corporation, 2023; Moody's Investors Service, 2023). Philadelphia restructured stormwater billing around impervious surfaces and gross areas, creating a stable revenue stream for the Green City, Clean Waters program (Philadelphia Water Department, 2022).

These cases separate two questions that green finance often merges. A bond can be green because of its use of proceeds, but it is bondable because of its repayment source. Case D addresses

the second question. The selected cases meet the Revenue Sufficiency Condition independently of their green designation.

4.13. Analysis Against Framework Variables

Pricing autonomy and contract stability derive from bond covenants. Water and sewer utilities set rates through administrative processes designed to recover costs and fund capital investment (Beecher, 2013). Bond documents convert that authority into contractual commitments: DC Water, NY State EFC, and Philadelphia covenant to maintain rates sufficient to cover approximately 1.20x to 1.35x debt service (DC Water, 2016; New York State Environmental Facilities Corporation, 2023; Philadelphia Water Department, 2022). A concession contract and a bond covenant use different legal forms, but both create revenue visibility across the financing horizon (Yescombe, 2014).

Demand durability and political durability are jointly supported by essential-service characteristics. Households and businesses cannot easily substitute away from water, sewer, and stormwater systems, and price elasticity is low for basic use (Beecher, 2013). That demand structure supports strong ratings for NY State EFC, DC Water, and Philadelphia. Political durability is reinforced because suppressing rates below covenant levels would create technical default, trigger bondholder remedies, and impair future market access (Moody's Investors Service, 2023).

4.14. Findings

The cases show the self-financing chain from user-fee revenue to green bond issuance. Investment-grade ratings can be achieved without public debt when the revenue stream itself is

creditworthy. The green designation describes the use of proceeds; it does not describe the credit quality of the underlying asset. Philadelphia's stormwater fee also shows that a revenue stream designed specifically for green infrastructure can satisfy the Revenue Sufficiency Condition where rate-setting authority, essential-service demand, and bond covenants are present.

Table 6. Green Revenue Bond Case Studies: Coverage Ratios, Ratings, and Infrastructure Financed

Criterion	DC Water EIB (2016)	NY State EFC	Philadelphia Water
Revenue Mechanism	Water and sewer user fees	Water and sewer user fees	Stormwater utility fee
Instrument	Environmental Impact Bond (first US EIB)	Revenue bonds (AAA-rated)	Revenue bonds and CWSRF loans
Bond Rating	Investment grade (Aa2, Moody's)	AAA (S&P and Moody's)	A (S&P)
Debt Service Coverage	≥1.35x (covenant)	≥1.25x (statutory)	≥1.20x (covenant)
Green Infrastructure Financed	Green stormwater infrastructure citywide	Water quality and watershed protection	Green stormwater infrastructure; impervious fee reform
Public Subsidy Required	No	No	No

Sources: DC Water Environmental Impact Bond Official Statement (2016) and Annual Reports; NY State EFC Annual Reports and Moody's and S&P Rating Surveillance; Philadelphia Water Department Annual Financial Reports and Green City, Clean Waters Program Reports; MSRB EMMA public data. All data is publicly available.

4.15. Boundary Cases and Framework Limits

Research context and background

The affirmative cases demonstrate self-financing where the necessary and sufficient conditions are present. Two negative cases test the boundary. British Rail tests the framework where pricing autonomy is structurally foreclosed on a high-demand corridor. The Dulles Greenway tests the framework where demand durability proves insufficient despite a long concession and partial rate-setting authority.

The British Rail franchise model, created after the 1993 Railways Act, privatized operations through time-limited franchises. Regulated fare caps applied to most fare categories, and shortfalls were backstopped through the Passenger Service Requirement mechanism. The East Coast Main Line, despite strong demand, returned to public operation three times after operator financial failure rather than demand collapse (National Audit Office, 2018).

The Dulles Greenway is a fourteen-mile privately financed toll road in Northern Virginia that opened in 1995 under a forty-year concession. The operator could set tolls only with Virginia State Corporation Commission approval and within a rate-of-return cap. Traffic projections anticipated 20,000 vehicles per day at opening and 87,000 by 2010, but actual demand fell far below those expectations (Bipartisan Policy Center, 2019; U.S. Department of Transportation, Build America Bureau, 2014).

Analysis against framework variables

Pricing autonomy was absent in British Rail by design. Fare caps prevented operators from raising prices to recover rising operating costs. The East Coast Main Line had high and relatively

captive demand, but the regulatory architecture placed R(t) below the level required to cover D(t) + O(t) + V(t). Three successive operators failed under the same constraint, showing that the failure was institutional rather than operator-specific (National Audit Office, 2018).

The Dulles Greenway reflects a joint failure of demand durability and partial pricing autonomy. Traffic volumes were roughly seventy percent below projections, and parallel free routes captured demand the financial model assumed would pay tolls (U.S. Department of Transportation, Build America Bureau, 2014). When demand underperformed, the operator's ability to raise prices was constrained by the rate-of-return cap (Virginia Department of Transportation, 2019). Debt restructurings followed in 1999 and 2005, debt accumulated through zero-coupon instruments, and the concession term was extended to 2056 to prevent insolvency (Blankingship and Keith, 2025). The case shows that when demand durability fails, pricing flexibility is the backstop; where that backstop is also constrained, revenue sufficiency fails.

4.15.1. Findings

The negative cases produce two findings. Pricing autonomy is necessary; high demand cannot substitute for it, as British Rail shows. Demand durability is also necessary; long contracts and partial rate authority cannot substitute for captive demand at cost-recovery prices, as the Dulles Greenway shows. The Dulles Greenway additionally demonstrates compounding failure: demand underperformed, and pricing constraints removed the operator's primary response mechanism.

Cross-Case Synthesis

Across Sections 4.1 through 4.5, the cases span six decades, four countries, three revenue mechanisms, and outcomes ranging from uninterrupted self-financing to chronic subsidy dependence and program suspension. Four findings recur.

First, mechanism type matters less than institutional protection. JCDecaux, HCTRA, DC Water, and Stockholm use different revenue logics, but all share pricing autonomy, contract stability, demand durability, and political durability. British Rail fails despite strong demand, confirming that demand volume and mechanism type are insufficient without institutional protection.

Second, the payer need not be the beneficiary. Transit riders receive JCDecaux infrastructure at no direct charge, while advertisers pay for access to those riders. This extends self-financing beyond user charges to cases where direct cost recovery would be regressive, politically unacceptable, or infeasible.

Third, pricing autonomy and contract stability are present in every self-financing case and absent or weakened in every failure case. British Rail fails because fare caps foreclose pricing autonomy; Dulles Greenway fails because constrained pricing cannot compensate for weak demand; and NYC congestion pricing fails because executive action suppresses the revenue mechanism before operation.

Fourth, political durability is independent of financial design. NYC had statutory pricing authority, durable demand, and investment-grade projections but failed before collecting revenue. In every successful case, reversal imposes a measurable cost on the political actor; in New York, no equivalent institutional cost existed. These findings support the formal framework in Section 5.

5. 5. Framework Boundaries and Structural Limitations

Three classes of infrastructure fall outside the framework's boundary regardless of institutional design quality. Identifying them is as important as identifying which assets pass the

Revenue Sufficiency Test, because misclassifying an asset in either direction produces the wrong policy response.

Low-density geographies cannot meet the Revenue Sufficiency Condition under either mechanism. User-charge models require demand volume sufficient to cover fixed costs; below that threshold, cost-recovery prices become politically or socially unsustainable. Third-party models require audience scale sufficient to attract advertisers; below a footfall threshold, regulatory exclusivity cannot compensate for weak demand. Empirical estimation of these density thresholds — the minimum viable footfall for third-party models and the minimum traffic volume for user-charge models — is a future research task.

Low-income communities present a distributional constraint that institutional design cannot fully resolve. The Bogotá valorization system illustrates the boundary: at its 1968 peak, it funded sixteen percent of local public expenditures, but schemes in lower-income areas were deliberately priced below cost recovery because beneficiaries could not sustain full charges (Doebele, Grimes, and Linn, 1979). The Revenue Sufficiency Condition failed not because of weak design but because the social constraint on pricing was legitimate. Where that constraint binds, public subsidy is the correct policy response — not a structuring failure but a recognition that not every infrastructure need can be self-financed at socially acceptable prices.

Pure public goods are entirely outside the framework. Nonexcludable, non-rival assets — flood levees, open-access green space, biodiversity protection — cannot generate R(t) through user-charge or third-party mechanisms. Calling their investment gap, a structuring problem is a category error; it is a public funding problem. One of the more persistent misdiagnoses in infrastructure finance is treating assets in this category as if better contract design would unlock private capital. It would not. The usefulness of the Revenue Sufficiency framework is partly in identifying which assets fall here and therefore where public finance is not substitutable.

Table 7. Revenue Sufficiency Calibration: Framework Predictions and Observed Outcomes

Case	NC1	NC2	NC3	NC4	SC met	Predicted	Observed
JCDecaux	Yes	Yes	Yes	Yes	Yes	Self-financing	€3.57B 2023; zero public subsidy
Indiana Toll Road	Yes	Yes	Yes	Yes	Yes	Self-financing	USD 3.8B concession; zero subsidy since 2006
407 ETR	Yes	Yes	Yes	Yes	Yes	Self-financing	Zero public subsidy since 1999
HCTRA	Yes	Yes	Yes	Yes	Yes	Self-financing	Aa3; zero general fund support
Stockholm CC	Yes	Yes	Yes	Yes	Yes	Self-financing	SEK 900M annually; funds road investment
London CC	Yes	Yes	Yes	Yes	Yes	Self-financing	£1.5B cumulative net; funds TfL
DC Water EIB	Yes	Yes	Yes	Yes	Yes	Self-financing	Aa2; zero public operating subsidy
NY State EFC	Yes	Yes	Yes	Yes	Yes	Self-financing	AAA; unbroken debt service coverage
Philadelphia Water	Yes	Yes	Yes	Yes	Yes	Self-financing	A; stormwater fee funds green infrastructure

NYC Congestion Pricing	Yes	Yes	Yes	Yes	No (political durability)	Failure	Program suspended; zero revenue collected
British Rail (East Coast)	Yes	No (pricing autonomy)	Yes	Partial	No	Failure	Chronic subsidy dependence; three operator failures
Dulles Greenway	Yes	Partial	No	Yes	No	Failure	Debt restructuring; no equity distributions since 2006

NC1 = identifiable revenue mechanism. NC2 = pricing autonomy. NC3 = demand durability. NC4 = contract stability. SC = sufficient conditions (political durability, appropriate risk allocation, bondability). CC = congestion charge. EIB = Environmental Impact Bond. EFC = Environmental Facilities Corporation.

The framework predicts all eleven cases consistently, including the three failures. The three failures each isolate a distinct variable. British Rail tests absent pricing autonomy on a corridor where demand was not the problem. The Dulles Greenway tests demand durability failure with partial pricing autonomy — the two weaknesses compounded each other. NYC tests absent political durability despite all four structural conditions being present; the financial model was intact when the program was suspended. No case produces self-financing without the necessary conditions, and no case fails when all necessary and sufficient conditions are present.

Case selection bias could skew our results and warrants further research. Assets that failed the necessary conditions were often structured as subsidy-dependent from the outset and therefore never generated observable self-financing failures. The most informative negative cases may be invisible because they never reached market. Resolving this problem requires a prospective dataset of potential self-financing assets evaluated against the framework before outcomes are observed. That dataset does not currently exist and is a priority for future research.

A case of self-financing without the four necessary conditions, or failure despite all necessary and sufficient conditions, would require revision. No case in the current dataset meets that falsification criterion, and the consistency across asset types, jurisdictions, and six decades of data support using the framework as an analytical and design tool.

6. 6. Implications for Climate Finance

6.1. Self-Financing Infrastructure as an Asset Class

Revenue-sufficient sustainable infrastructure shares the characteristics institutional investors are seeking, such as long asset lives, predictable cash flows, inelastic or essential-service demand, protected pricing, and low asset-level correlation with broader cycles (Yescombe, 2014). NY State EFC's AAA rating, HCTRA's Aa3 rating, and JCDecaux's investment-grade corporate debt show that capital markets already recognize these characteristics in specific structures. These assets are not concessional impact investments; they are revenue-generating infrastructure with measurable risk profiles (Beecher, 2021).

This reframing matters for capital mobilization. Pension funds, sovereign wealth funds, and insurers allocate to infrastructure because of duration, income generation, and inflation linkage, not just environmental and social impact.

6.2. Implications for Green Bond Design

The Revenue Sufficiency Framework identifies an important distinction within the green bond market: bonds whose green character comes from the use of proceeds and bonds whose bondability comes from the revenue sufficiency of the repayment source. This distinction affects structuring, pricing, and credit analysis.

A green bond backed by an asset that meets the necessary and sufficient conditions can be structured, priced, and rated on revenue fundamentals without public credit backstop. DC Water's Aa2 rating, NY State EFC's AAA rating, and Philadelphia Water's A rating reflect revenue-stream creditworthiness rather than a public guarantee. Conversely, a green bond backed by an asset

missing one or more conditions requires targeted support, such as a guarantee, first-loss piece, or blended finance structure, calibrated to the absent condition. Structuring support against the specific weakness preserves market discipline while reducing unnecessary public intervention.

6.3. Implications for PPP Contract Design

The institutional design variables identified in Sections 2 through 5 translate directly into PPP contract provisions. The framework can function as a checklist for governments structuring concessions and investors evaluating proposed PPPs.

Pricing autonomy is the most critical contractual variable. Concession agreements should specify the pricing mechanism and include protections that shift the cost of politically motivated rate interference to the public sector through liquidated damages, change-in-law compensation, or step-in rights. Rate-of-return caps create asymmetric constraints, as the Dulles Greenway demonstrates.

Contract length should reflect the ratio of capital expenditure to operating cash flow and the debt financing horizon, not political preference for shorter terms. The Dulles Greenway's later forty-year extension illustrates the fiscal cost of underestimating horizon needs. Bond covenants, as used by DC Water and HCTRA, can provide equivalent revenue certainty where concession contracts are not the right institutional form (Yescombe, 2014).

Political durability protections should match the jurisdiction's risk profile. Referenda can legitimize novel charges, as in Stockholm. Fiscal interdependence can make reversal costly, as in London. Revenue sharing can create a public-sector constituency for continuation, as in JCDecaux. The common design principle is that reversal must impose a direct cost on the actor able to reverse the revenue stream.

6.4. The Capital Mobilization Agenda

The global infrastructure financing gap cannot be closed by public budgets alone. Climate adaptation and mitigation needs compound that gap, and the dominant policy response has been to

demand more grants, concessional capital, and multilateral support. The Revenue Sufficiency Framework identifies a different constraint for a bounded category of assets: where the necessary and sufficient conditions are present, the binding constraint is not capital availability but institutional design.

Private institutional capital exists at a sufficient scale to finance revenue-sufficient sustainable infrastructure. Global pension assets exceeded USD 55 trillion in 2023 (OECD, 2024), and infrastructure allocations have grown because the asset class offers long-duration, income-generating characteristics. The constraint is the supply of investable assets structured with pricing autonomy, demand durability, contract stability, and political protection. Institutional design converts latent capital supply into actual infrastructure investment.

This has direct implications for public intervention. Credit enhancement for assets that could become revenue-sufficient through better institutional design substitutes scarce public capital for reform. Credit enhancement for assets that genuinely fail the necessary conditions because of structural demand insufficiency, distributional constraints, or public goods characteristics is appropriate. The framework identifies which category an asset belongs to and therefore where public finance is substitutable and where it is necessary.

6.5. Equity and Access Considerations

The framework is a tool for capital mobilization and bondability. It does not optimize equity of access, geographic coverage, or distributional justice, and it does not claim that market-based infrastructure finance is socially optimal in all contexts.

User-charge mechanisms can be regressive when users have a lower income than the general population. Stormwater fees, tolls, and congestion charges impose larger burdens as a share of income on lower-income households (Beecher, 2021; Pandey, Brelsford, and Seto, 2022). Bogotá's valorization system illustrates the limit: lower-income areas were deliberately priced below cost recovery because beneficiaries could not sustain full charges, requiring general revenue

transfers (Doebele, Grimes, and Linn, 1979). In such cases, public subsidies are not a failure of the framework but the correct policy response.

The geographic distribution of self-financing infrastructure raises a similar concern. The cases in Section 4 are concentrated in dense, high-income urban environments with mature legal and capital-market institutions. The conditions that support revenue sufficiency are systematically more available in wealthy urban centers than in lower-income or lower-density jurisdictions. Infrastructure inequality is a documented feature of urbanization (Pandey, Brelsford, and Seto, 2022), and communities most in need of investment may be least able to generate bondable revenue streams.

The parallel to market-based technology deployment is instructive. Fu et al. (2025) show that large language models trained on historical planning data may reproduce spatial bias by favoring affluent neighborhoods. Market-based infrastructure finance carries a similar risk: investment flows toward high-demand, high-income corridors where revenue conditions are easiest to satisfy, while lower-income areas remain dependent on constrained public subsidies. Equity objectives therefore require deliberate public intervention rather than reliance on market mechanisms alone.

7. 7. Conclusion

7.1. Summary of Findings

Sustainable infrastructure is often treated as a public good requiring recurring subsidies (Aschauer, 1989; Gramlich, 1994). This paper shows that treatment is appropriate for much of the infrastructure universe but not for every asset. A bounded category of sustainable infrastructure can achieve revenue sufficiency when four necessary conditions are present: an identifiable revenue mechanism, pricing autonomy, demand durability, and contract stability. Three sufficient conditions then convert potential self-financing into reliable self-financing: political durability,

appropriate risk allocation, and bondability. The absence of any necessary condition predicts failure, and political durability remains independently necessary even when the financial model is sound.

The four propositions are supported by the case evidence. P1 is supported because pricing autonomy appears in every self-financing case and is absent or weakened in cases where revenue sufficiency failed. P2 is supported because long-term contracts, covenants, or statutory structures make future revenue streams underwritable by capital markets. P3 is supported by the JCDecaux recovery trajectory and institutional analysis, although direct elasticity testing against digital substitutes remains an avenue for future empirical work. P4 is supported by the New York City congestion pricing case, where financial viability was demonstrably present but political durability was absent, resulting in suspension prior to first toll collection.

The framework makes three theoretical contributions. First, the payer need not be the beneficiary. Mohring-Harwitz established self-financing through user charges; this paper extends the logic to third-party revenue mechanisms, where advertisers fund infrastructure used by transit riders. Second, mechanism type matters less than institutional protection. JCDecaux, HCTRA, Stockholm, and DC Water use different revenue logics, but all protect the revenue stream through pricing autonomy, contract stability, demand durability, and political durability. Third, this paper proposes that revenue-sufficient assets can both attract capital on financial merits without public subsidies while also providing environmental and social benefits to society.

7.2. Limitations and Future Research

Four limitations define the next stage of research. First, the framework is calibrated against cases from high-income countries with mature institutional environments. The conditions that support revenue sufficiency, including long-horizon contracts, deep advertising markets, and revenue-bond capital markets, are more available in wealthy urban centers. Testing in developing-country and lower-income contexts is required before broader generalization.

Second, the dataset is subject to observational selection bias. Assets that failed the necessary conditions were often structured as subsidy-dependent from the outset and never generated observable self-financing failures. A prospective dataset of potential self-financing assets evaluated before outcomes are known would be the strongest next empirical contribution.

Third, causal identification requires a design that isolates the effect of individual institutional conditions on outcomes. The case evidence establishes consistent prediction but not causal precision. A panel study across asset classes and jurisdictions could test the falsifiable proposition that self-financing should not occur without all four necessary conditions and should not fail where all necessary and sufficient conditions are present.

Fourth, two theoretical extensions are priorities. The first is a formal model of the endogeneity between pricing autonomy and political durability, especially where user charges impose regressive burdens. The second is a theory of the third-party revenue mechanism, specifying the minimum footfall, advertising market depth, and regulatory capacity required for the model to replicate across different urban forms.

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