RENEWABLE ENERGY INTEGRATION INTO METRO INFRASTRUCTURE: A COUPLED MODEL OF LOCALIZATION AND DECARBONIZATION

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Abstract. Photovoltaic deployment on metro infrastructure is normally justified on decarbonization grounds alone. This paper argues that in an emerging economy it should be assessed simultaneously as an industrial-localization instrument, and that on this second criterion it outperforms the sector's conventional localization vehicle — rolling-stock manufacturing. Using the design parameters of a 150 MW, 270.2 GWh/year project attached to a metro operator, the study benchmarks the scheme against international cost references and decomposes its expenditure by tradability. The implied capacity factor of 20.6% exceeds the 2023 global weighted average of 16.2%, while specific capital cost of 773 USD/kW is within 2% of the global weighted average of 758 USD/kW. Approximately 55% of capital expenditure and some 90% of lifetime operation and maintenance spending fall on non-tradable inputs — structures, cabling, civil works, installation and services — giving a lifetime domestic value share near 68%, against 25–35% for imported rolling stock and 50–65% for rolling-stock modernization. The policy implication is that this domestic share requires no local content mandate and therefore incurs none of the cost penalties documented for mandated localization of tradable components.

Keywords: localization, decarbonization, metro infrastructure, solar photovoltaics, local content requirements, non-tradable inputs, capacity factor, industrial policy.

Urban rail operators in emerging economies pursue two policy objectives that are usually managed separately. The first is decarbonization and energy-cost control; the second is industrial localization — raising the domestic share of the goods and services the system consumes. Investment appraisal typically treats a photovoltaic programme under the first heading and rolling-stock manufacturing under the second. This paper

argues that the separation is an analytical error, and that once expenditure is decomposed by tradability the photovoltaic programme emerges as the stronger localization instrument of the two.

The argument is developed on the design parameters of a solar programme attached to a metro operator: an installed capacity of 150 MW, annual generation of 270.2 GWh, and total capital expenditure of 116 million USD, with sites distributed across depot roofs, planned car parks and an adjacent land parcel. Two benchmark checks establish whether these parameters are plausible before any conclusion is drawn from them (Table 1).

Table 1

Benchmarking the project parameters against international reference values[1]

Parameter	Project value	Global reference, 2023	Deviation
Installed capacity, MW	150	—	—
Annual generation, GWh	270.2	—	—
Specific yield, kWh/kWp per year	1 801	—	—
Implied capacity factor, %	**20.6**	16.2 (weighted average)	**+4.4 p.p.**
Total installed cost, million USD	116	—	—
Specific capital cost, USD/kW	**773**	758 (weighted average)	**+2.0%**

The capital-cost check is reassuring: at 773 USD/kW the scheme sits within two per cent of the 2023 global weighted average for utility-scale photovoltaics, so the investment figure is not inflated. The yield assumption is more demanding. An implied

[1] *Author's calculation from the project design parameters; reference values from IRENA [1].*

capacity factor[2] of 20.6% stands 4.4 percentage points above the global weighted average. High irradiance in the region makes such a value attainable, but not with fixed-tilt mounting; it presupposes single-axis tracking or an equivalently optimistic performance ratio. The generation figure should therefore be treated as an upper bound until confirmed by measured on-site irradiance data.

The localization argument turns on a distinction that the local content literature makes but that project appraisal rarely applies: the difference between tradable and non-tradable inputs. Mandated localization of tradables is expensive. Probst et al. [2] show that local content requirements in the Indian solar auctions raised generation costs by roughly six per cent per kilowatt-hour, and Stone, Messent and Flaig [3] find that such requirements depress exports in sectors well beyond the one targeted. Those findings concern modules and cells — internationally traded, scale-intensive goods in which a small domestic market cannot compete. They say nothing about the remainder of a photovoltaic project, which is not traded at all.

That remainder is substantial. Decomposing utility-scale photovoltaic expenditure along the cost categories used by IRENA [1] — modules, inverters, balance-of-system hardware[3], installation and soft costs — places roughly 45% of capital expenditure on imported equipment and the balance on mounting structures, cabling, transformers, civil works, installation labour and project services (Table 2). None of these can be imported economically: they are produced where the plant is built, by definition.

Table 2

Decomposition of photovoltaic expenditure by tradability[4]

Cost component	Share of CAPEX, %	Character	Sourcing
Modules	35–40	tradable	imported

[2] The capacity factor is the ratio of actual annual generation to the output that would be produced at rated capacity for every hour of the year: 270.2 GWh / (150 MW × 8 760 h) = 20.6%. The global weighted average for utility-scale photovoltaics commissioned in 2023 was 16.2% [1].

[3] Balance of system denotes all plant components other than the modules themselves — mounting structures, cabling, combiner boxes, transformers and grid-connection equipment — together with the associated civil and electrical works.

[4] *Author's estimate based on the cost-component structure reported by IRENA [1]. Shares are indicative and project-specific.*

Cost component	Share of CAPEX, %	Character	Sourcing
Inverters and power electronics	5–8	tradable	imported
Mounting structures and racking	10–13	non-tradable	domestic
Cabling, transformers, grid connection	12–15	mixed	mainly domestic
Civil works and installation	12–15	non-tradable	domestic
Soft costs: design, permitting, management	12–18	non-tradable	domestic
Domestic share of capital expenditure	**≈ 55**	—	**≈ 63.8 mln USD**

Operation and maintenance strengthens the effect further. At an indicative 17.5 USD per kW per year over a twenty-five-year life, maintenance spending amounts to some 65.6 million USD — comparable in magnitude to the capital cost of the plant — and is almost entirely local, since it consists of cleaning, inspection, electrical servicing and civil upkeep. Taking capital and operating expenditure together, the lifetime domestic value share of the programme reaches approximately 68%.

The comparison with rolling stock is the point of the exercise (Figure 1). Purchasing imported metro cars yields a domestic share of roughly 25–35%, most of it in delivery, commissioning and warranty servicing. Modernization of existing cars performs considerably better, at 50–65%, because the labour and component content is domestic. Photovoltaic capital expenditure matches modernization at about 55% and exceeds it over the asset lifetime. Critically, the rolling-stock figures are attainable only with sustained technology transfer, supplier development and certification investment, whereas the photovoltaic figure requires none of these: it follows from the physical nature of the expenditure.

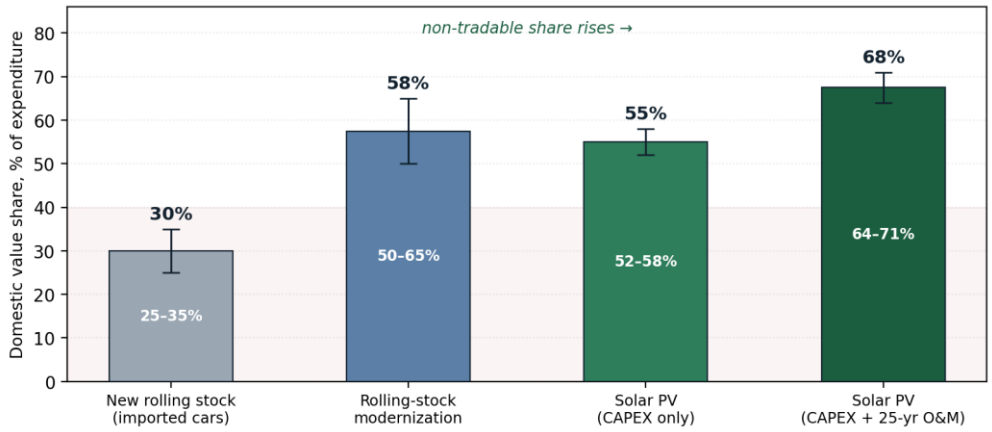


Figure 1. Domestic value share by type of capital programme available to a metro operator[5]

Three implications follow. First, decarbonization capital should be entered into the localization ledger rather than assessed separately; excluding it understates the domestic content the operator is already generating. Second, the sequencing of local content policy should distinguish the two categories: mandates applied to modules would reproduce the cost penalties documented in the literature [2; 3], while the non-tradable share needs no mandate and can be captured through procurement design alone — lot structuring, prequalification of domestic fabricators and bundled long-term maintenance contracts. Third, the maintenance stream deserves explicit contractual attention, since it is the largest and most durable domestic component and the one most easily surrendered to a foreign turnkey provider through an inattentive tender.

Two limitations should be stated. The cost shares in Table 2 are indicative ranges rather than project accounting, and the split of generation between self-consumption and grid export is left out of scope, because the available operating-cost data on the operator's electricity consumption are internally inconsistent[6] and cannot support a self-supply ratio. Neither limitation affects the tradability argument, which rests on the physical composition of the expenditure rather than on its financing.

In conclusion, photovoltaic investment in metro infrastructure should be understood as a coupled instrument. It reduces emissions and exposure to tariff escalation, and it simultaneously delivers a higher domestic value share than any

[5] *Compiled by the author. Rolling-stock ranges reflect reported modernization and procurement practice; photovoltaic values from Table 2 and the operation-and-maintenance estimate.*

[6] Available operating reports give electricity as 18% of total costs in one place and 25–30% in another, and the monthly expenditure figure implied by the second is inconsistent with the reported payroll. Reconciling these series is a prerequisite for any self-supply calculation and is left to subsequent work.

rolling-stock programme available to the same operator — without a local content mandate, and therefore without the efficiency losses that such mandates impose. For emerging-economy operators facing both a decarbonization obligation and an industrial-localization target, this is the rare case in which the two are not in competition for the same capital.

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