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Thermo-economic principles to assess the global economic sustainability of solar photovoltaics

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ABSTRACT

Thermodynamic limits are intrinsically insurmountable, whereas economic limits may be disregarded without infringing any physical laws, provided societies accept the resulting economic consequences. This study is rooted in the existence of a limited sustainable range of long-run energy-expenditures to Gross-Domestic-Product ratios. Instances exceeding affordability thresholds signal heightened risk of economic downturn. Within this framework, we investigate whether photovoltaics can expand without pushing economies beyond the Bashmakov-Newbery range of energy-expenditures, identified as globally sustainable. Using gross-domestic-product, primary energy, and energy intensity data, we analytically derive an affordability corridor of (94 ± 20)\$/BOE for primary energy and (38 ± 8)\$/GJ for electricity. A new conception of global-economic-sustainability becomes essential, as energy conversion systems operating above the affordability threshold would undermine prosperity. As no thermodynamic imperative enforces declining energy prices limits, we formulate a normalized thermo-economic efficiency index that links thermodynamic and economic principles within an original simulation framework, enabling assessment of whether photovoltaics complies with the global economic sustainability constraints. Incorporating capital, technological and maintenance costs, the model sets the global-economic-sustainability benchmarks for photovoltaics, across residential, solar-community, and utility-scale sectors, including storage and booster-reflector setups. Results indicate that, to produce electricity within the global economic sustainability requirements, utility-scale photovoltaics can follow a pure unsubsidized pathway even quite ahead of their lifetime horizon. When storage is included, costs approach their critical threshold, unless favorable long-term projections are assumed. Booster-reflectors can aid solar projects to reach global economic sustainability. By contrast, residential sector faces critical scenarios, even over the entire lifetime horizon, being dominated by significant soft-costs.

1. Introduction

Energy security and affordability have repeatedly shaped global economic and policy agendas since the late twentieth century. The OPEC oil embargo of 1973 following the Yom Kippur war demonstrated the vulnerability of modern economies to abrupt increases in energy costs [1]. These shocks triggered a wave of research into the relationship between energy prices, energy intensity, and macroeconomic performance [2]. Empirical evidence shows consistently that the share of income spent on energy remains within a constrained long-term band. When this share rises above the band, recessions and structural adjustments often occur as highlighted by studies of Bashmakov et al. [3] about the laws of energy transition, the relation between energy consumption and economic growth [4] supported by empirical evidence, theory and policy implications [5]. When the share falls innovation and efficiency gains occur [6]. This empirical regularity has been increasingly formalized, justifying the concept of an upper energy price limit, here denoted as $K_{\$}$, compatible with Global Economic Sustainability (GES) [7].

The rise of renewable energy technologies must therefore be evaluated not only on their technical progress but also on their ability to deliver useful energy within macroeconomic affordability limits. Among all alternatives, solar power rapidly emerged as the most promising due

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Nomenclature

Symbol-acronym-abbreviation	Meaning, Unit
PV	Photovoltaic, –
GES	Global Economic Sustainability, –
GDP	Gross Domestic Product, $
NREL	National Renewable Energy Laboratory, –
IEA	International Energy Agency, –
IEA-PVPS	IEA Photovoltaic Power Systems, –
IRENA	International Renewable Energy Agency, –
BOS	Balance of System, –
ESS	Energy Storage System, –
USD	United States Dollar, –
η	Conversion efficiency, –
η_{exp}	Experimental/actual system conversion efficiency, –
$\eta_{lim,ec}$	Economic lower-bound efficiency (from macro constraint), –
η_n	Normalized thermo-economic index, –
d	Discount rate, –
n_s	Horizon time, year
α	O&M / overhead fraction, –
Y	Annual energy yield per installed W (AC), MWh W^{-1} yr^{-1}
Y_{eff}	Effective yield per W including performance ratio and reflectors, MWh W^{-1} yr^{-1}
φ_s	Annual solar irradiation (plane of array), GJ m^{-2} yr^{-1}
ψ_s	Average solar power density, W m^{-2}
ϕ_{stc}	STC irradiance, Wm^{-2}
N_{pk}	Annual peak-sun hours, hyr^{-1}
K$ (K$, generic)	electricity price limit (macro affordability), $ MWh^{-1}
$K_{\$,min}, K_{\$,max}$	Lower/upper bound of sustainable electricity price range, $ MWh^{-1}
MUP	Maximum Unit Price for primary energy, $ kWh^{-1}
MSP	Minimum Sustainable Price (benchmark in NREL reports), $ W^{-1} or $ kWh^{-1} (as per context)
EI	Primary Energy Intensity (primary energy / GDP), kWh $\$^{-1}$ or GJ $\$^{-1}$
EI^{-1}	Energy Productivity (GDP per unit energy), $ kWh^{-1}
ECS	Energy Cost Share of GDP (Bashmakov–Newbery band) % of GDP
$C_{H,1W}$	Hardware cost per W (modules, inverters, structural, electrical BOS), $ W^{-1}
$C_{S,1W}$	Soft cost per W (permitting, interconnection, customer acquisition, overhead), $ W^{-1}
D1, D2, D3, D4	Feasibility domains in efficiency-cost plane, –
$a_{r,c} = A_R/A_C$	Reflector-to-collector area ratio, –
γ	Specific cost factor of booster reflectors (per Wp of conventional PV), –
EF_b	Energy enhancement factor due to booster reflectors, –
b	Booster configuration, –

to its scalability and abundance. Since the first practical silicon solar cell was demonstrated at Bell Labs in 1954 efficiency has increased nearly fivefold as shown in the tabulated values by Rühle [8]. The record for single junction silicon devices is ~ 27.4 %, close to the Shockley–Queisser limit of ~ 33 % [9]. As this physical limit is approached, the marginal rate of efficiency improvement inevitably slows [10]. Silicon remains the dominant technology with about 90 % of global installations [11]. The dramatic decline in module prices since 2010 has enabled cumulative installed capacity to exceed 2 TW worldwide [12]. Yet the pace of deployment remains insufficient to align with net zero trajectories.

Future cost reductions will be required not only from continued improvements in cell efficiency but also to offset the costs of managing variability and intermittency. For this reason, advanced cell architecture is under intense investigation. Heterojunction devices and perovskite–silicon tandems now exceed 30 % efficiency in laboratory demonstrations [13]. Perovskite technologies are especially attractive because of their rapid efficiency gains, low temperature fabrication, and use of abundant materials [14]. In just over a decade their efficiency increased from ~ 4 % to ~ 27 % for single junctions and ~ 35 % for tandems [15]. However, instability under light, heat, and moisture still limits their lifetimes. Progress has been made in encapsulation, interface engineering, and consensus testing protocols, but operational durability is still insufficient for widespread commercialization [16].

In parallel, extensive Life-Cycle Assessment (LCA) literature confirms that photovoltaic technology is environmentally sustainable over its operational lifetime. Comparative LCA studies and *meta*-analyses show that the environmental footprint of Photovoltaics (PV) systems has declined steadily as conversion efficiencies have increased and manufacturing process has shifted to cleaner energy sources. Recent reviews, article and technical document report energy payback times of about 1–2 years and carbon footprints between 25 and 40 g CO_2-eq kWh^{-1}, values far below those of fossil-based generation [17]. These results demonstrate that, from an environmental perspective, solar PV achieves net positive energy and carbon balances early in its lifetime, thereby reinforcing the macro-economic rationale for its large-scale deployment.

Scaling PV to the levels required for deep decarbonization involves technical and non-technical barriers beyond modules. The variability of solar radiation requires expensive storage and flexibility resources to maintain reliability [18]. Fossil power plants often remain in operation longer than expected, delaying substitution. Supply chains for key raw materials are volatile [12]. Land use conflicts and the challenge of integrating PV into built environments present further constraints [19], with more critical challenges in countries not fully developed, like those in the African continent [20]. This is clearly just one of the most critical aspects related to the delicate balance between sustainability, energy transition and circularity as highlighted in ref. [21]. Consequently, projections of PV's contribution in 2030 and 2050 differ widely depending on assumptions about technology, integration costs, and policy support [22]. System level benchmarking shows clearly why scale matters. While hardware costs have fallen sharply, soft costs – permitting, interconnection, financing, and customer acquisition – dominate residential projects. These costs are proportionally lower in community scale projects and the lowest at utility scale both in 2023 [23] and in 2024 [24]. Studies about the Levelized Cost Of Energy (LCOE) and storage confirm that PV plus storage remains less attractive than PV, unless storage costs decline substantially or flexibility services are fully valued. To this end, global battery pack prices declined to about 115 USD/kWh in 2024 [25,26], but integration remains economically challenging [22]. Financing conditions further amplify these effects, since discount rates and payback times strongly influence levelized cost estimates [23].

Optical augmentation strategies provide another incremental option. High albedo reflectors and engineered ground covers can raise bifacial yields by 3–5 % depending on geometry and latitude [27]. Dynamic reflective devices and booster reflectors reshape generation profiles and enhance performance, particularly at the community scale, for both photovoltaic systems—demonstrated by feasibility studies on flat boosters [28] and a case study in Sweden [29]—and solar thermal generation [30]. Experimental studies confirm that even modest gains can influence feasibility for borderline projects [31–33]. In particular, Baccoli et al. presented an optimization model based on experimental data [31], simulation model [32] or theoretical model of a solar collector augmented by a flat plate [33].

Other research works address the integration of PV at high penetration levels. Analyses of curtailment, declining market value, and adequacy requirements show that system integration costs can erode competitiveness if not accounted for [34]. Studies of ancillary services and operational flexibility highlight the importance of storage and flexible demand in maintaining value [35]. These insights demonstrate that affordability cannot be assessed solely through module or system costs but must incorporate system level interactions.

Perhaps the most robust strand of evidence concerns macroeconomic regularities. Early studies established that the share of Gross Domestic Product (GDP) devoted to energy expenditures remains relatively stable over time and across countries [36]. Later research confirmed that values above 10–12 % are typically unsustainable [37]. This stability has been described by the three laws of energy transitions [38] and more recently formalized as the "minus one" elasticity linking energy prices to energy intensity [5]. The implication is that sustainable energy technologies must deliver services within affordability bands, or they risk undermining growth [7].

When all these literature studies are considered together several important insights emerge, but also some fragmentation. Technology reviews document efficiency progress and device bottlenecks both in terms of conversion efficiency [39] and material and device research [40]. In particular, optical augmentation studies illustrate modest but sometimes decisive yield benefits [41]. Regarding the economic aspects, benchmarking studies highlight the persistence of soft costs [23] showing also that levelized costs are highly sensitive to financing and resource conditions [42]. In a more global perspective, macroeconomic analyses define affordability bands based on long run empirical data [38]. Despite their richness, these strands remain disconnected, leaving unresolved how to unify macroeconomic evidence with the techno-economic evaluation of concrete PV system designs [6].

From the available evidence three major research gaps are clear. First, there is still no compact method to determine whether a given PV configuration, distinguished by scale and by options such as storage or reflector augmentation, can be deployed at a price consistent with long run affordability bands. Existing studies either analyze technology metrics without embedding them in macro constraints or examine macro affordability without translating it into practical system thresholds [43]. Second, there is no normalized thermo-economic index that integrates physical conversion efficiency with an economic lower bound efficiency derived from empirical expenditure bands. Without such a metric comparability across studies remains limited and conclusions are often context dependent [43]. Third, many applied analyses provide incomplete assumptions about discount rate, payback time, system boundaries, or resource conditions, and often omit systematic sensitivity analysis to the most influential parameters including soft costs, storage prices, and resource availability [42]. This limits reproducibility, robustness, and policy relevance.

The present article seeks to address these shortcomings. The objective is to define a normalized thermo-economic efficiency index that embeds macroeconomic constraints directly into feasibility analysis. To the best of the authors' knowledge, this is one of the first studies that aims to translate the long run stability of the energy expenditure band into an explicit upper price limit for electricity, denoted as $K_{\$}$, and to incorporate this limit into a unified framework. This framework allows systematic evaluation of PV systems across residential, community, and utility scales, including both configurations with and without storage and with and without reflector augmentation. By combining macroeconomic constraints with technology performance and cost parameters, the framework provides a compact test of whether a specific PV design is consistent with the GES constraints. This approach does not replace conventional metrics such as LCOE but complements them by introducing macro affordability as an explicit criterion.

The novelty lies in unifying previously separate strands of literature. Technology and benchmarking studies identify cost and performance trends but not macro limits. Macroeconomic research quantifies affordability bands but does not link them to specific system designs. Integration studies describe system costs but without embedding them in affordability ranges. Optical augmentation experiments show performance enhancements but without positioning them against sustainability thresholds. This article aims to combine these perspectives within a single normalized index. The analysis offers a reproducible method for testing PV feasibility against empirically observed macroeconomic constraints. It clarifies under what conditions, and at which scales PV remains consistent with sustainable energy expenditure levels. It also identifies where barriers remain, such as the heavy weight of soft costs in residential PV, the current expense of storage, and the moderate (but sometimes relevant) contributions of reflectors. By embedding the macroeconomic perspective directly into the system evaluation, this contribution provides both a conceptual advance and a practical tool for policymakers and system planners.

The remainder of the article is structured as follows. Section 2 introduces the methods, including the analytical formulation and the definition of the normalized thermo-economic index. Section 3 describes the input parameters and analyzed scenarios, based on the most recent cost benchmarks and field data. Results are reported for residential, community, and utility-scale systems, considering configurations with and without energy storage and reflector augmentation. Section 4 draws some conclusions with also focusing on limitations and directions for future work.

2. Methods

In this section, the methods of the article are developed. An original thermo-economic model of the PV (with or without booster equipment and with or without storage), by introducing the normalized thermo-economic efficiency index and the derivation of the upper and lower bounds of the electricity price based on the perspective of the Global Economic Sustainability, is presented. The main assumptions adopted are:

- Unique value of electricity price for selling PV energy or avoided cost of buying electricity, as this methodology has a macroscopic view, and the threshold energy price value can be seen as an averaged value between self-consumed and sold energy;
- Steady-state analysis, justified by the scale and the global perspective of the applications of the method. Hourly data are only used to calculate the solar availability.
- A baseline discount rate equal to 4 %, slightly lower than 5 % commonly used in the renewable energy sector, to reflect a more global perspective rather than project-specific financing conditions. However, a sensitivity analysis by varying the discount rate is presented in Section 3.4.

2.1. *Conventional photovoltaic system (without booster equipment)*

An economic analysis for conventional solar PV technology system can be settled by considering the expression in Eq. (1). This is derived from fundamental correlation between economic and energy aspects involved in the PV solar technology. The expression highlights the conditions in which the thermodynamic conversion efficiency η_{exp} allows to generate useful renewable energy matching the economic efficiency rate $\eta_{lim,ec}$, based on the principle of the GES. The interested readers are invited to refer to Appendix A of the supplementary material, where the mathematical procedure, culminating in Eq. (1), is explained. Basically, in Appendix A, the global economic balance for a conventional PV system (Eq. 1A) is shown by requiring that annual revenues exceed investment and O&M costs, once the time horizon (like the payback period) and discount rate are fixed. This condition is reformulated (Eq. (2A)) as a minimum annual energy yield per m^2, expressed through the conversion efficiency and annual solar irradiance (Eq. (3A)), with O&M costs proportional to revenues (Eq. (4A)). Finally, by relating costs per surface area to costs per unit peak power (Eq. (6A)), the model arrives at Eq. (7A), which matches Eq. (1) in the main manuscript.

$$\frac{\eta_{lim,ec}}{\eta_{exp}} = \eta_n \geq \frac{\sum_{j=1}^{n_s}(1+d)^j}{{n_s}^2} \bullet \frac{(C_{H,1W}+C_{S,1W}) \bullet \phi_{stc}}{K_\$ \bullet \varphi_s(1-\alpha)} \tag{1}$$

Practically, the inequality expressed in Eq. (1) represents an analytical criterion in the plane of efficiency and cost coordinates $\{C_{H,1W}, \eta_n\}$, as shown in Fig. 1. It identifies the coordinates $\{C_{H,1W}, \eta_n\}$ for which a given PV power plant proves to be consistent or not with the requirements of the GES' s principle.

η_n is a normalized thermo-economic efficiency index. It is derived by combining the economic lower limit efficiency coefficient, $\eta_{lim,ec}$, with the actual experimental energy conversion efficiency coefficient of the PV system.

$\boldsymbol{\eta_{lim,ec}}$ represents a lower-bound efficiency threshold, defined by economic feasibility constraints that keep energy expenditures within globally sustainable limits.

Therefore, a square meter of solar conversion system operating at an efficiency lower than the admissible value $\eta_{lim,ec}$ would generate insufficient energy per unit area to cover its overall costs (manufacturing, installation, operation, and maintenance) when the electricity price is constrained to the lower bound $K_\$$.

$\boldsymbol{\eta_{exp}}$ represents the experimental thermodynamic conversion efficiency of the PV plant, commercially rated during standard operating conditions.

$(\mathbf{C_{H,1W}} + \mathbf{C_{S,1W}})$ is the unit cost per peak of direct current output power. It represents the cost share sustained by the source of the capital for purchasing, installing, and starting – up a solar converter power plant accounted for per peak of power unit of its collecting surface. In particular, $C_{H,1W}$ includes the subsystem costs for modules, inverters, Energy Storage System (ESS), structural and electrical BOS, while soft costs components as fieldwork, office-work and other soft costs are incorporated in the $C_{S,1W}$ term. The values, in $[\$/W]$, are drawn from refs. [23,24].

α is related to the operating and maintenance costs of the PV system converter, $C_{O\&M}$. Such costs can be thought of as driven by the total income provided by selling the energy good production. Specifically, α represents the fraction of the monetary income to be allocated for covering the operating and maintenance costs per peak of PV power unit. The value is a dimensionless quantity and is numerically drawn from [23,24].

$\boldsymbol{n_s}$ is the simple pay-back time of the whole system composed of collecting converting-surfaces and auxiliary elements as inverter and electrical adapter device or a generic time horizon. Its value is expressed in number of years, $[y]$.

$\boldsymbol{d}$ is the yearly discount rate of investment. This value, for general energy-related investments, is fixed at 4 %, as already specified above.

$\boldsymbol{\varphi_s}$ represents the Solar Resource Assessment and denotes the yearly available amount of the total radiant exposure, per square meter of collectable surface, expressed in $\left[GJ/m^2y\right]$. It is derived from the number N_{pk} of the equivalent peak hours sun that, on average, are yearly available, in a given geographical location. Such values are usually reported in published standard documents focused on solar resource assessment for evaluating a location's potential for solar energy. The values of N_{pk} are determined referring to standard operating conditions for which the solar irradiance standard value is equal to $\phi_{stc} = 1000$ $\left[W/m^2\right]$. Therefore,

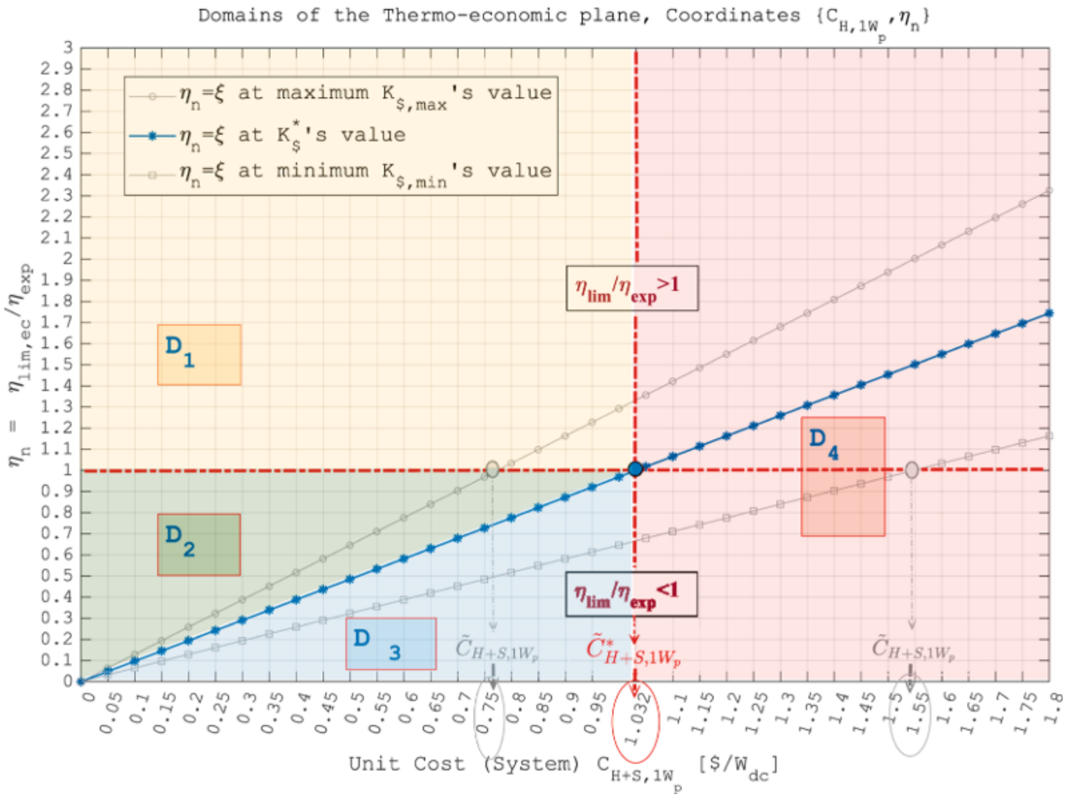

Fig. 1. Thermo-economic plane of efficiency-cost domains to identify the boundary of GES requirements.

$$\{\varphi_s\}\cdot\left[\frac{GJ}{m^2y}\right] = \{\phi_{stc}\}\cdot\left[\frac{W}{m^2}\right] \bullet \{\mathrm{N}_{pk}\}\cdot\left[\frac{h}{y}\right]\cdot\{3600\}\cdot\left[\frac{s}{h}\right]\cdot\frac{10^9}{10^9}$$
$$= \{\phi_{stc}\} \bullet \{\mathrm{N}_{pk}\}\cdot\left\{\frac{3,600}{10^6}\right\}\cdot\left[\frac{GJ}{m^2\cdot y}\right] \tag{2}$$

Each physical quantity, (φ_s, ϕ_{stc} and N_{pk}), is expressed, accordingly to ISO 80000-1, as a product of a pure number, representing the magnitude ($\{\varphi_s\}$, $\{\phi_{stc}\}$ and $\{\mathrm{N}_{pk}\}$), and the respective measurement unit.

Finally, $\boldsymbol{K}_\$$ is the maximum admissible monetary remuneration value derived by selling the energy production generated by the solar system or by the avoided cost of buying electricity from the national grid. This value should be consistent with the community's economic growth as it should align with the affordability range of energy expenditures identified as sustainable at a global level. An energy price higher than $K_\$$, while reducing the expected payback time n_s, may slow down the overall productive system by increasing energy costs and potentially constraining GDP growth. Its value is expressed in $[\$/GJ]$ or $[\$/MWh]$.

Fig. 1 illustrates the proposed normalized index η_n as a function of $C_{H+S,1W_p}$, for different values of $K_\$$. The graphs are represented in the efficiency-cost plane of coordinates $\{\mathrm{C}_{\mathrm{H+S,1W_p}}, \eta_\mathrm{n}\}$ and can be selected by changing the value of $\mathrm{K}_\$$, within a given $[\mathrm{K}_{\$,\mathrm{min}} \div \mathrm{K}_{\$,\mathrm{max}}]$ range, whose values will be assessed later. The curves with the steepest gradient are obtained for the smallest values of $\mathrm{K}_\$$. Each curve represents a thermo-economic locus composed of points whose $\{\mathrm{C}_{\mathrm{H+S,1W_p}}, \eta_\mathrm{n}\}$ values result in the left hand of Eq. (1) equal to its right hand. Here, both constraints required by GES are marginally satisfied: a) the system produces energy at an adequate rate for generating a not negative yearly profit for the source of the capital and b) the energy production is sold at a price within the range of energy expenditure – GDP ratio, identified as sustainable at a global level. The right-hand side of Eq. (1) can be thought of as a monotonically increasing function of the unit cost $C_{H+S,1W_p}$, namely $\xi(C_{H+S,1W_p})$. A maximum unit cost can be identified, above which the GES requirements cannot be satisfied. For any $K_\$$, there is a critical unit cost threshold where the ξ function is 1. This critical value is graphically visualized with the symbol $\widetilde{C}_{H+S,1W_p}$. Generally, the lower the energy expenditure value (identified as globally sustainable), the lower the critical cost of the PV installation. All unit cost values, exceeding the critical one, are in correspondence to ξ function values larger than 1. For all these values, the inequality Eq. (1) would pose a normalized economic efficiency value larger than 1.

$$\eta_n > 1 \tag{3}$$

It is interesting to explore the meaning of the previous condition in terms of GES. By definition,

$$\eta_{lim,ec} > \eta_{exp} \tag{4}$$

By definition, Eq. (4) defines a constraint that is physically unattainable: it requires the sale of more energy than the PV system can produce. The producible amount is determined by the experimental conversion efficiency η_{exp} whereas the required sales are governed by the economic limit efficiency $\eta_{lim,ec}$. GES requirements, expressed by Eq. (1), establish a lower bound for η_n, while physical feasibility imposes an upper bound, $\xi \leq \eta_n \leq 1$. For $C_{H+S,1W_p} > \widetilde{C}_{H+S,1W_p}$, Eq. (1) reduces to Eq. (4), leading $\eta_n > 1$ and hence to an infeasible GES region.

Fig. 1 also illustrates how the efficiency-cost plane is divided into four different domains when a specific value of $\mathrm{K}^*_\$$ is accounted for. The horizontal red dashed line, representing the upper limit value of η_n, given by the equation $\eta_n = 1$, the starred blue curve and the vertical red line (expressed by equation $\boldsymbol{C}_{\boldsymbol{H+S,1W_p}} = \widetilde{\boldsymbol{C}}^*_{\boldsymbol{H+S,1W_p}}$) divide the efficiency – cost plane into four domains D_1, D_2, D_3 e D_4 described by the following conditions.

$$\begin{cases} D_1 = \left\{\eta_n > 1, C_{H+S,1W_p} < \widetilde{C}^*_{H+S,1W_p}\right\} \\ D_2 = \left\{\xi \leq \eta_n \leq 1, C_{H+S,1W_p} < \widetilde{C}^*_{H+S,1W_p}\right\} \\ D_3 = \left\{0 \leq \eta_n \leq \xi, C_{H+S,1W_p} < \widetilde{C}^*_{H+S,1W_p}\right\} \\ D_4 = \left\{\eta_n \geq 0, C_{H+S,1W_p} > \widetilde{C}^*_{H+S,1W_p}\right\} \end{cases} \tag{5}$$

D_1 is the region bounded below by the constant function curve given by η_n equal to 1 and is composed by η_n values strictly larger than the unit value. Based on the previous considerations, it is clear that D_1 domain is inconsistent with GES conditions since it is physically not feasible (despite unit cost is lower than critical one). D_2 is the region bounded below by the ξ function curve, above by the constant function curve η_n equal to 1 and rightward by unit costs lower than the critical one. The region is the only one compatible with the GES requirements, where both economic constraints are simultaneously satisfied. When η_n equates the ξ values, the GES requirements are marginally satisfied. When $\eta_n = 1$, the system reaches its maximum economic value, as determined by experimental conversion efficiency. The comprised values correspond to an intermediate remuneration. D_3 covers the region bound below by the constant function curve η_n equal to 0 and above by the $\xi(C_{H,1W_p})$ function curve. In this region the η_n values are lower than the ξ values. Therefore, the fundamental inequality Eq. (1) is not satisfied. It represents the domain of economic unsustainability. The requirement on the expected monetary consideration for the source of capital would be unsatisfied, unless the energy production is sold at a price exceeding the maximum economically tolerable $K_\$$ value. This condition spurs the adoption of specific subsidizing schemes for supporting solar energy applications and their advancement and adoption in energy plan context. High-cost solar technologies should be balanced with lower-cost energy sources to prevent average energy prices from exceeding levels that could hinder economic prosperity. Under these conditions, clarifying whether the primary priority is mitigating environmental impacts or avoiding economic hardship caused by excessively high energy prices represents a necessary preliminary step. Finally, D_4 includes the region bounded leftward by the inequality $C_{H,1W_p}$ larger than the critical one, $\widetilde{C}_{H,1W_p}$. In this region the GES is economically unfeasible, as already observed for D_1 domain, since the unit costs are associated with ξ values larger than 1.

2.2. Booster reflectors-augmented photovoltaic system

Previous equations and considerations for analyzing GES of conventional PV system configurations, can be extended, under the same perspective to the analysis of booster reflectors-augmented PV—collectors. Mathematical derivation is presented in Appendix A. The final equation of the present model is the following:

$$\left.\frac{\eta_{min,ec}}{\eta_{exp}}\right|_b = \eta_{n,b} \geq \frac{\sum_{j=1}^{n_{s,b}}(1+d)^j}{{n_{s,b}}^2} \bullet \frac{(C_{H,1W} + C_{S,1W}) \bullet (1 + a_{r,c} \bullet \gamma) \bullet \phi_{stc}}{K_\$ \bullet \varphi_s \bullet (1 + \mathrm{EF}_b)(1 - \alpha_b)} \tag{6}$$

The structure of Eq. (6) is clearly similar to that of Eq. (1). The main difference is the presence of the enhancing effect provided by an augmented PV system and the additional costs involved in the booster's equipment. The adopted subscript "b" refers to the "boost" provided by such an augmented PV system. Furthermore, a few additional terms are defined:

- $\boldsymbol{a_{r,c}}$ represents the ratio between the reflector and the collector area, $\mathrm{A_R}/A_C$.
- $\mathbf{EF}_{\boldsymbol{b}}$ represents the enhancement factor which provides a figure of the augmentation effect of the reflector on the collector energy production. Its general definition can be expressed by the ratio of energy

production associated with the boosted PV collectors over the energy associated to the conventional one.

- γ is related to the unit cost for purchasing, installing, and starting – up booster reflectors' equipment accounted for per peak of power unit of conventional PV system. Specifically, γ can be meant as the proportional fraction of the unit cost related to the conventional PV system. It is a dimensionless quantity and its value will be determined later.

Clearly, adding booster reflectors to PV collectors with the aim of reducing the overall system's payback time would not be economically justified on its own. In fact, it may be more reasonable to invest those resources in expanding the PV surface area. Therefore, the feasibility of an augmented system must be assessed under the condition that:

$$\mathrm{n}_{s,b} < n_s \quad (7)$$

where $\mathrm{n}_{s,b}$ and n_s represent the payback time of the augmented and conventional PV systems, respectively. To solidify our ideas, let's consider and combine (1) and (6) for determining the conditions for which the booster reflector equipment contributes to reducing the payback time and its minimization. The payback time $\mathrm{n}_{s,b}$ of the augmented PV system can be expressed as a function of the payback time n_s of the system without booster equipment, as shown by the following:

$$(\mathrm{n}_{s,b})^2 = (\mathrm{n}_{s,c})^2 \bullet \mathscr{H}, with \mathscr{H} = \left[\frac{1+\gamma \bullet a_{r,c}}{(1+\mathrm{EF}_b)}\right] \quad (8)$$

Eq. (8) allows us to evaluate the economic feasibility of the booster project, for which the additional costs, to allocate for equipping collectors with booster reflectors, prove to be balanced or exceeded by the enhancement factor effect. As long as $\mathscr{H} < 1$, implying that $\gamma \bullet a_{r,c} < \mathrm{EF}_b$ is lower than 1, the payback time of the augmented system is lower than that of the "conventional" system. Conversely, if $\mathscr{H}$ is greater than 1 $(\gamma \bullet a_{r,c} > \mathrm{EF}_b)$ the economic feasibility of the augmented PV plant can be compromised. The case $\mathscr{H} = 1$ $(\gamma \bullet a_{r,c} = \mathrm{EF}_b)$ represents the marginal feasibility threshold. The cost function y_{cost} shows a linear dependence on the reflector to collector area ratio $a_{r,c}$, with a slope governed by γ, while the enhancement factor EF_b exhibits a nonlinear dependence on $a_{r,c}$, as determined experimentally or analytically in Refs. [31–33].

In this study, EF_b is determined experimentally as a function of $a_{r,c}$. Several experiments were carried out over two-year measurement period, testing five different reflectors to collector area ratios, ranging from $a_{r,c} = 0.5$ to $a_{r,c} = 3$. The manufacturing phase and related techno-economic details of the reflectors are provided in Refs. [31–33]. Both the conventional and augmented systems were installed on the flat roof of the Solar Energy Laboratory at the Institute of Technical Physics, University of Cagliari (Latitude: $\Phi = 39^\circ 16' 24.13''$, north hemisphere, Longitude: $\Lambda = 9^\circ 7' 32.75''$, Est). Both solar systems were subjected to identical environmental conditions and globally optimized. In particular, for both units, surface angular positions and reflector dimensions were designed according to optimal values predicted by the second optimization criterion formulated in Ref. [31–33]. Selected experimental results comparing the performance of conventional and augmented PV systems are presented in Appendix B of the supplementary material (Figs. B1–B20). These figures confirm that increasing the collection capacity using flat specular reflectors significantly enhances power output, depending on $a_{r,c}$. The measured values of EF_b, averaged over yearly periods for each $a_{r,c}$ are plotted in Fig. 2. The same figure also shows the cost function $y_{cost} = \gamma \bullet a_{r,c}$. A specific value of $\dot{a}_{r,c}$ exists at which the difference $\mathrm{EF}_b - y_{cost}$ is maximized. At the same time, this optimal ratio $\dot{a}_{r,c}$ minimizes the payback time of the augmented system and depends on the slope γ. The parameter γ quantifies the relative cost of boosting a conventional PV system. Based on consolidated literature dealing with boosted systems, as demonstrated by refs. [28,29,41,44–51], a realistic value for γ is approximately 10 % of the overall cost of a conventional PV plant. The case $\gamma = 0.9$ is plotted in Fig. 2, considering optimal reflector – collector angular adjustments. This is supported by extensive prior studies [31–33] and market surveys on commercial reflectors, which considered the trade-off between reflectivity, efficiency, and cost. The cost of commercial reflector technologies is primarily influenced by spectral properties, as reported in specific studies [51–55]. The cost per square meter $C_{R,1m^2}$ can be linearly related to the global reflectivity ϱ as follows:

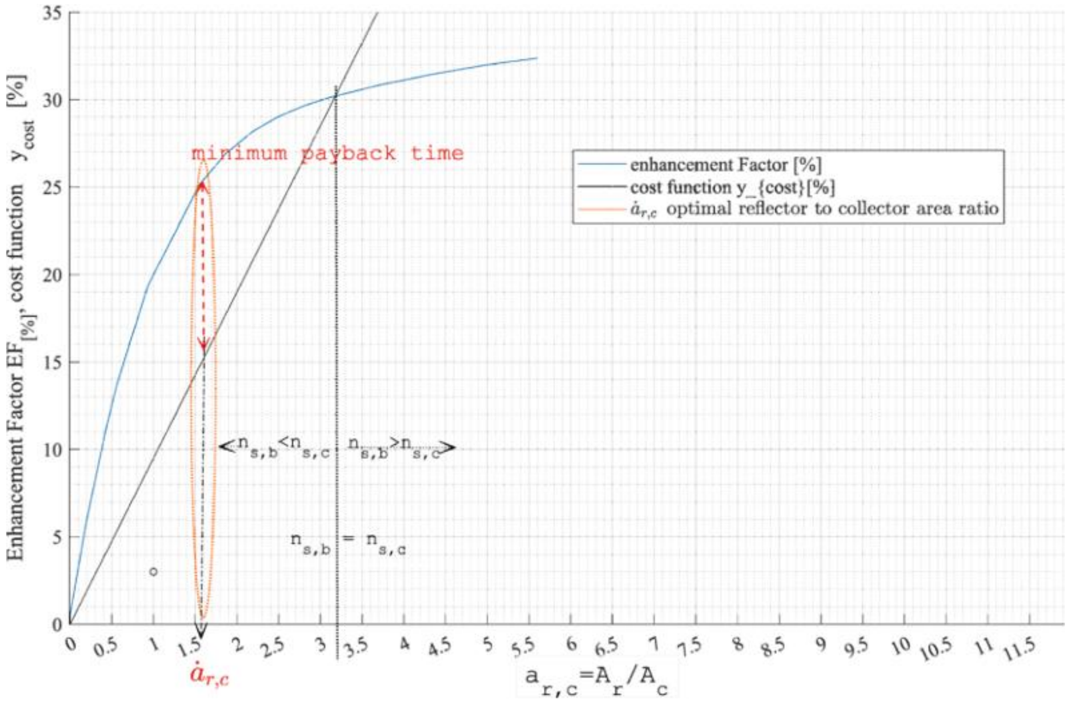

Fig. 2. Comparison between the cost function $\mathrm{y_c}(\mathrm{a_{r,c}}) = \gamma \bullet \mathrm{a_{r,c}}$ and the experimental enhancement factor $\mathrm{EF_b}(\mathrm{a_{r,c}})$, as a function of the reflector to collector area ratio $\mathrm{a_{r,c}}$.

$$C_{R,1m^2}[\$/m^2] = (105.67\varrho - 69.816) \tag{9}$$

High-reflectivity materials are preferred for their durability and contribution to enhanced power output. In this study, reflectors were made from anodized aluminum with an extra-bright surface ($\varrho = 0.93$), selected for its excellent mechanical and thermal properties, making it ideal for long-term PV booster applications [56]. The unit cost $C_{R,1m^2}$ including mounting elements, varies with the plant scale: approximately 61 \$/m^2 for small-scale installations and 22 \$/m^2 for utility-scale. These cost ranges correspond to γ values centered around 10 % relative to the total PV system cost.

2.3. Estimation of the economic parameters

The conceptual scheme developed above can be applied to commercial PV solar technology to shed some light on its global economic sustainability. All parameters involved in Eqs. (1) and (6) need to be quantified. It can be easily observed that the values influencing the quantities $\mathrm{n_s}$, $n_{s,b}$, d, φ_s, μ, α, γ, EF_b, $a_{r,c}$ and $K_\$$ may fall within a numerical range, rather wide. Specific economic parameters, as $C_{H,1W}$, α, μ, γ are drawn from the last reports (2024, 2023) of U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks (With Minimum Sustainable Price Analysis) [23,24]. The most appropriate numerical values are chosen according to the GES. More specifically, when official reports, or data taken from the available literature are not available in the form of a single deterministic value, the most conservative values are selected to evaluate the Global Economic Sustainability. Furthermore, a sensitivity analysis is conducted by varying the discount rate, the effective number of solar operating hours, and the investment time horizon in order to assess their influence on the results.

The enhancement factor EF_b is experimentally determined and validated in this study through a new measurement campaign. Our experimental results validate previously reported literature values [41,57–66] and are consistent with the authors' prior modeling work [31–33].

2.3.1. Relation between affordable ranges of energy cost share to gross domestic product ratio and sustainable energy price $\mathrm{K}_\$$

The maximum economically sustainable unit price ($K_\$$) for energy is derived from the concept of a sustainable range for economy-wide energy expenditures relative to GDP. According to existing literature, the Energy Cost Share to GDP ratio (ECS_{GDP}) – defined as the ratio of total consumer expenditures on final energy (including taxes and subsidies but excluding non-fuel use) to national GDP – represents the annual proportion of GDP spent on energy consumption in market economies. This ratio varies among nations and circumstances.

Empirical studies highlight that elevated energy expenditures relative to GDP signal a heightened risk of economic recession. Over the past 50 years, OECD economies have demonstrated a clear correlation between high energy expenditures and economic downturn (see Appendix C of the supplementary material for more details). Significant surges in energy expenditures occurred during the first (1973–74) and second (1979–80) oil crises, both preceding widespread recessions. A similar trend was observed leading to the global financial crisis starting in the early 2000s, peaking around 13 % in both 2008 and 2022. The only notable exception was the pandemic-affected year of 2020.

Several studies [6,7,67,68], based on long-term correlations between economic and energy time series from global datasets spanning more than a century, provide empirical evidence for the existence of a sustainable range of long-run energy expenditures. This range tends to gravitate toward approximately $4.2 \pm 0.8\%$ of Gross Output, corresponding to about $7.2 \pm 1.5\%$ of GDP. The available literature termed these limits as the "Bashmakov-Newbery" range. Periods of stable economic conditions typically see developed and populous nations, including OECD members, China, and India, allocating less than 8 % of GDP to energy expenditures. Exceeding this threshold generally raises concerns due to recessionary risks. Supplementary figures to support such a discussion are provided in Appendix C.

A central aspect of this study is to establish the underlying relationship between the Bashmakov–Newbery sustainable expenditure range, expressed as a percentage value of GDP, and the upper sustainable unit energy price $K_\$$ (expressed in \$/GJ or \$/MWh). The global Energy Intensity (EI) index serves as a bridge between GDP and $K_\$$. The EI index is defined as the primary energy consumption per unit of GDP. These values adjusted for inflation and purchasing power parity. The goal of such adjustments is to provide purchasing power, fixed over time and across countries, so that one international dollar can buy the same quantity and quality of goods and services no matter where or when it is spent. GDP is measured in international-\$ at 2011 prices.

The EI index incorporates the Equivalent Primary Energy consumption (EPE) which is calculated applying the substitution method. In this approach, non-fossil sources are adjusted as if subjected to fossil-fuel conversion efficiency losses, based on a standardized thermal efficiency factor (typically set at approximately 0.40 at international level). The EI index (kWh/\$) provides insight into efficiency of the global economic system, with its reciprocal value indicating how much GDP (in monetary terms) is generated per unit of consumed energy. It accounts for an absolute theoretical upper limit for energy unit price, representing the Maximum Sustainable energy Price (MUP) achievable if the entire GDP were hypothetically dedicated to purchasing primary energy inputs required by the economy. Therefore,

$$\mathrm{EI}^{-1}[\mathrm{kWh_{th.}}/\$]^{-1} = \mathrm{MUP}[\$/\mathrm{kWh_{th.}}] \tag{10}$$

$$\mathrm{MUP}[\$/\mathrm{kWh_{th.}}] \bullet \mathrm{EPE}[\mathrm{TWh_{th.}}] = 100\%\mathrm{GDP}[\$] \tag{11}$$

Multiplying both sides of Eq. (11) by the value of the sustainable percentage ranges of Bashmakov and Newbery, the following relation can be obtained.

$$\mathrm{ECS_{GDP,B-N}}[\%] \bullet \mathrm{GDP}[\$]/(\mathrm{EPE}[\mathrm{TWh_{th.}}]) = \mathrm{ECS_{GDP,B-N}}[\%] \bullet \mathrm{MUP}[\$/\mathrm{kWh_{th.}}] \tag{12}$$

where the first hand of equation Eq. (12) represents the ratio of the sustainable amount of energy-expenditure over the Equivalent Primary Energy. Therefore, the second hand represents the maximum unit price of energy that proves to be economically tolerable for the economic system:

$$\begin{aligned}\mathrm{ECS_{GDP,B-N}}[\%] \bullet \mathrm{MUP}[\$/\mathrm{MWh_{th.}}] &= \mathrm{ECS_{GDP,B-N}}[\%] \bullet \mathrm{EI}^{-1}[\mathrm{kWh_{th.}}/\$]^{-1} \\ &= \mathrm{K_{\$,th}}\end{aligned} \tag{13}$$

In 2023, the average value of the world energy intensity index was approximately 1.3 $[\mathrm{kWh_{th}}/\$]$. This value corresponds to an upper price limit of energy MUP equal to about 770 $[\$/\mathrm{MWh_{th.}}]$. As the Bashmakov-Newbery limits span from 7.2 ± 1.5 % of GDP, Eq. (13) returns an average economically sustainable maximum unit price around 55 $[\$/\mathrm{MWh_{th}}]$, with a minimum of 44 $[\$/\mathrm{MWh_{th.}}]$ and a maximum of 67 $[\$/\mathrm{MWh_{th.}}]$. Expressing these sustainable values in terms of \$/BOE (barrel of oil equivalent) allows meaningful comparison with daily economic experience. The sustainable price range corresponds numerically to oil prices approximately between \$75 and \$114 per BOE, with an average value of \$94/BOE. Recent economic hardships correlated with oil prices surpassing \$120 per barrel reinforce this observation, and economic recovery typically occurs when oil prices settle below \$100 per barrel. Consequently, a reference range for the maximum tolerable primary energy cost could reasonably be assumed as \$(94 ± 20)/BOE or equivalently (55 ± 12) $\$/\mathrm{MWh_{th}}$. Since this analysis specifically relates to the primary energy cost, adjustments must be made to account for conversion efficiencies when applying the analysis to electricity generation systems. Using a standard thermal-to-electrical efficiency factor of 0.40 from the substitution method, the corresponding sustainable electricity cost, $K_{\$,el}$ is estimated to be about 138 $\$/\mathrm{MWh_{el}}$, spanning a range from

108 \$/MWh$_{el}$ to 168 \$/MWh$_{el}$ (equivalently 30–47 \$/GJ). It should be emphasized that adopting an upper limit of 7.2 % of GDP, does not imply that all energy sources must individually remain below this cost. Rather, economic sustainability requires that higher-cost energy sources be offset by sufficiently lower-cost ones, so that the average energy cost across the system remains compatible with long-term economic prosperity.

2.3.2. Estimation of the photovoltaics-related parameters

The values of the input parameters $C_{H,1W}$, $C_{s,1W}$, μ and α of Eqs. (1) and (6) are addressed below. Accurate estimation and insight into the long-term trajectories of PV and storage system costs, for a wide range of typical configurations and installation practices, become essential to perform realistic economic analysis and prediction and to avoid a mistaken estimation of the global economic sustainability of a solar project. The two most recent NREL cost benchmark reports [23,24] provide detailed bottom-up cost estimates for all major components of PV and ESS systems, including permitting, site preparation, installation practices, and O&M activities. These benchmarks, based on U.S. national averages, may not reflect local market specifics. In addition to the conventional Modelled Market Price (MMP) approach, which focuses on near-term market and policy scenarios by disaggregating system costs under current market conditions, the NREL has introduced the Minimum Sustainable Price (MSP) model. This innovative methodology aims to capture long-term cost dynamics by filtering out short-term market fluctuations and policy-induced distortions. The MSP benchmark identifies the lowest viable prices at which suppliers can operate sustainably over the long term, incorporating minimal profit margins. To ensure long-term relevance, distorted short-term input costs are excluded, and each input is modeled at its minimum sustainable value. This makes the MSP model particularly suitable for long-term analyses and strategic R&D investment planning. Given these considerations, MSP-based data are more aligned with the goals of this study, whereas MMP-derived estimates may lack long-term reliability. Therefore, MSP values are adopted as the reference for the input parameters in Eqs. (1) and (6).

A flow chart useful to summarize the main steps of the proposed methodology is presented in Fig. 3.

3. Results and discussion

In this section, the results of an inter-comparison evaluation between different sizes and arrangements of PV-systems are discussed. Conventional PV-plus storage system and booster reflector-augmented collectors are analyzed in the residential, community solar and utility-scale sectors. The conditions for which these systems can be manufactured, installed, operated and maintained satisfying the constraints of the GES requirements are evaluated. Furthermore, sensitivity analysis considering variations on discount rate, solar availability (± 5 % with respect to the reference) for all the sectors and configurations are taken into account to demonstrate the robustness of the obtained results.

For each sector, four configurations are tested: PV only and PV + ESS, each in a conventional layout and with booster reflector augmentation. Costs are taken from the Minimum Sustainable Price (MSP) benchmarks released by NREL in Q1-2024. Financial inputs adopt payback targets consistent with the sector (8 years residential, 10 years community, 5 years utility) with a baseline discount rate of 4 %. Solar resource is represented by equivalent peak-sun hours aligned with typical siting for each scale (about 1500, 1700, and 2000 h yr^{-1}, respectively).

The three case studies are parameterized as follows. Residential sector presents a 8 kWdc rooftop PV array with 20.8 % monofacial modules and microinverters (DC/AC ≈ 1.21), optionally coupled to a 5 kW / 12.5 kWh lithium–ion battery. This is representative of the 4–16 kWdc range. Community scale presents a 3 MWdc fixed-tilt PV system with 20.5 % bifacial modules and string inverters (DC/AC ≈ 1.34), with an optional 1.8 MW / 7.2 MWh containerized battery. This brackets 1.5–6 MWdc projects. The Utility scale presents a 100 MWdc single-axis tracker plant with 20.5 % bifacial modules and string inverters (DC/AC ≈ 1.34), optionally paired with a 60 MW / 240 MWh battery. This represents the 50–200 MWdc class. Reflector augmentation uses an experimentally validated reflector-to-collector area ratio near 1.6 and a measured annual enhancement factor curve, with cost and performance grounded in prior experimental campaigns.

The interpretation of the plots is the same for all sectors. Each figure shows the normalized thermos-economic index η_n on the efficiency-cost

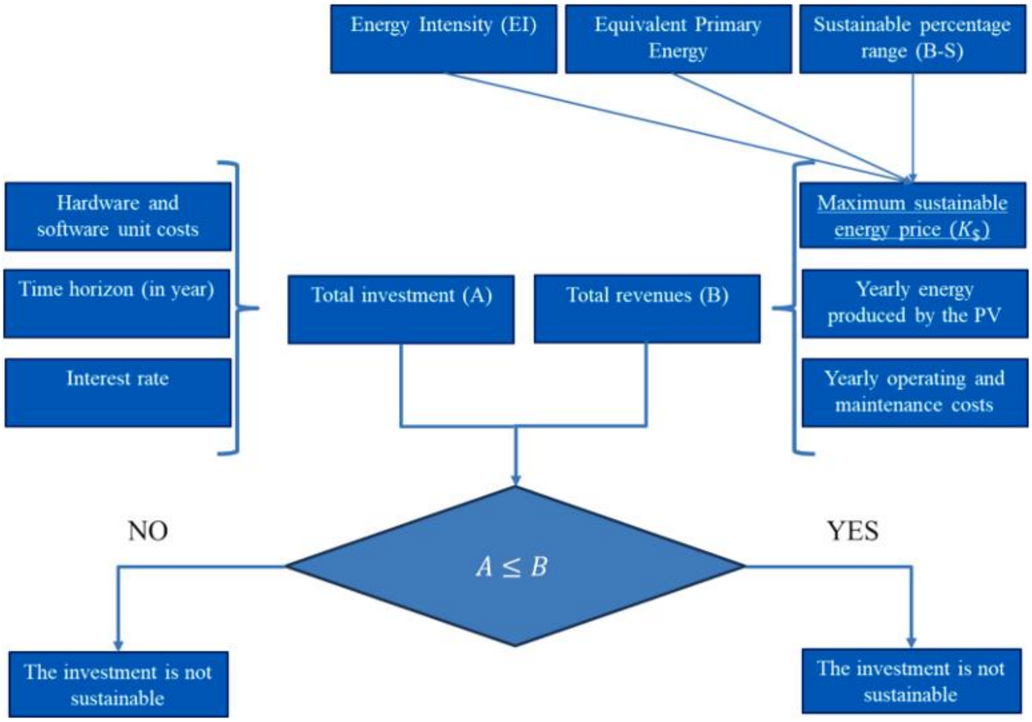

Fig. 3. Flow chart summarizing the proposed thermo-economic model.

plane. For a given $K_{\$}$ in the sustainable band (30–47 \$/GJ, equivalent to 108–168 \$/MWh), the locus $\eta_n = 1$ defines the critical unit cost $\widetilde{C}$ that marginally satisfies GES. If the MSP-based total unit cost lies below $\widetilde{C}$, the configuration is GES-compatible; if it lies above, it is incompatible. Reflector augmentation shifts the locus by increasing effective yield through the experimentally measured enhancement factor while adding a modest, scale-dependent reflector cost characterized by γ. ESS affects both CAPEX and O&M and, at current MSP values, typically steepens the η_n curve so that compatibility becomes harder to achieve.

All data about the technical specifications of the PV systems (with and without ESS and booster reflectors' equipment), installation, operations and maintenance cost items, solar availability and the financial conditions applied by the source of capital are summarized in Table 1.

3.1. *Residential sector*

Under 2024 MSP inputs, the normalized thermos-economic index η_n for residential PV without storage is above unity across the entire $K_{\$}$ range considered. In practical terms, the total unit cost sits above the critical cost curve, so GES is not satisfied. This is driven primarily by soft costs that dominate small projects which account for about 62 % in 2024 MSP. Fig. 4 (a) shows that unit cost trajectories continue to place the overall residential cost above the critical threshold across the affordable price range, confirming the structural gap. When storage is added, the gap widens. The PV + ESS configurations shift the total MSP cost further away from the GES-feasible region over the full $K_{\$}$ range as shown in Fig. 4(b). Results illustrate that $\eta_n > 1$, indicating that residential PV + ESS is economically unsustainable under the long-run affordability constraint unless storage costs fall markedly or the electricity price exceeds the GES band. Booster reflectors provide only incremental relief on this scale. The measured enhancement factors reported in prior optimization and field studies translate into small horizontal shifts of the η_n locus. These shifts are not sufficient to cross the critical boundary when soft costs dominate. The result is consistent with the engineering intuition that, at residential scale, administrative and customer-acquisition overheads rather than module-level yield are the binding constraint. Reflector augmentation can still be valuable for tuning profiles or improving borderline cases but is not transformative under current cost structures. The apparent contradiction with the rapid diffusion of residential PV in high-income countries is resolved by recognizing policy and tariff contexts. Many markets remunerate self-consumption at retail levels and socialize a portion of grid management costs in end-user tariffs. For households, the avoided bill may exceed the macro-affordable $K_{\$}$ used here, improving private paybacks even when the configuration does not satisfy GES. The framework in this paper keeps the average economic value constrained to the affordability band to test macro-consistency rather than private profitability. This distinction explains why residential adoption can expand under incentives while failing a strict GES test.

3.2. *Community solar sector*

Community solar occupies a middle ground between household systems and utility plants. Projects are large enough to capture procurement and construction economies of scale, yet small enough to interconnect at distribution level and serve a defined subscriber base. This scale advantage shows up in the cost structure. Hardware costs are materially below residential levels and soft costs, while still significant, are proportionally lower because developers spread permitting, interconnection, and customer-acquisition overheads across multi-megawatt installations. These structural differences largely explain why community PV without storage tends to satisfy the macro-affordability test over a broad portion of the sustainable electricity-price range $K_{\$}$. See Fig. 5 where the total MSP-based unit costs lie comfortably below the corresponding critical cost across most of the $K_{\$}$ band.

Policy and tariff design help reconcile the strong market momentum

Table 1

Solar photovoltaic and energy storage cost benchmarks, based on minimum sustainable price at Q1 2024 and Q1 2023. The costs are expressed in real USD 2023 and 2022, respectively. *Sustainable Unit Cost value of energy ranges between $K_{\$,min} = 108$ \$/MWhe, (equivalent to 30 \$/GJ) and $K_{\$,max} = 168$ \$/MWh (equivalent to 47 \$/GJ).

PV system without ESS unit	Residential		Community Solar		Utility-Scale	
System Size [W]	8 kWdc		3 MWdc		100 MWdc	
Solar Source Availability	$\psi_s = 171$[W/m^2], Npk = 1500[h/yr]$\varphi_S = 5.4$[GJ/m^{2}yr]		$\psi_s = 194$[W/m^2], Npk = 1700[h/yr]$\varphi_S = 6.12$[GJ/m^{2}yr]		$\psi_s = 228$[W/m^2], Npk = 2000 [h/yr]$\varphi_S = 7.2$[GJ/m^{2}yr]	
Min ÷ Max values of $\boldsymbol{K_{\$}}$ [\$/GJ] − [\$/MWh]	$K_{\$min} = 30$–108 $K_{\$max} = 47$–168		$K_{\$min} = 30$–108 $K_{\$max} = 47$–168		$K_{\$min} = 30$–108 $K_{\$max} = 47$–168	
ESS unit [W] ÷ [Wh]	5 [kW] ÷ 12.5 [kWh]		1.8[MW] ÷ 7.2 [MWh]		60 [MW] ÷ 240 [MWh]	
$\boldsymbol{a_{r,c} = A_r/A_c}$	1.6		1.6		1.6	
γ[%]	9		9		9	
Economic data						
Reference year	2023	2024	2023	2024	2023	2024
PV Hardware's Unit Cost, $C_{H,1W}$ [\$/Wdc]	0.95	1.03	0.59	0.64	0.56	0.59
PV Soft's Unit Cost, $C_{s,1W}$ [\$/Wdc]	1.38	1.7	0.89	0.70	0.41	0.39
$\boldsymbol{\mu = C_{s,1W}/C_{H,1W}/}$	1.45	1.65	1.5	1.1	0.73	0.67
Total Unit Cost [\$/Wdc]	2.34	2.74	1.48	1.34	0.97	0.98
PV's O&M Unit Cost $C_{op,1W}$[\$/$W_{dc}y$]	0.02878	0.02983	0.03982	0.02184	0.01611	0.01868
$(\boldsymbol{\alpha \cdot K_{\$}})\{[\$/\boldsymbol{GJ}],[\$/\mathbf{MWh}]\}$	5.32 ÷ 19.19	5.52 ÷ 19.89	6.51 ÷ 23.42	3.56 ÷ 12.85	2.32 ÷ 8.1	2.6 ÷ 9.34
α at $K_{\$min}$ [%]	17,8	18,4	21,7	11,9	7,5	8,6
α at $K_{\$max}$ [%]	11,33	11,8	13,8	7,6	4,8	5,5
Payback time n_s [y]	8	8	10	10	5	5
PV system + ESS unit						
PV + ESS Hardware's Unit Cost, $C_{H,1W}$ [\$/Wdc]	1.63	1.8	1.13	1.00	1.1	1.03
PV + ESS Soft's Unit Cost $C_{s,1W}$ [\$/Wdc]	2.25	2.7	1.19	0.99	0.55	0.7
$\boldsymbol{\mu = C_{s,1W}/C_{H,1W}}$**(PV + ESS)**	1.38	1.49	1.05	0.98	0.5	0.68
Total Unit Cost, [\$/Wdc]	3.88	4.49	2.32	1.99	1.65	1.73
PV & ESS's O&M Unit Cost $C_{op,1W}$[\$/$W_{dc}y$]	0.06128	0.07035	0.07525	0.04553	0.05073	0.04797
$(\boldsymbol{\alpha \cdot K_{\$}})\{[\$/\boldsymbol{GJ}],[\$/\mathbf{MWh}]\}$	11,3 ÷ 40,9	13,0 ÷ 46,9	12,3 ÷ 44,3	7,4 ÷ 26,8	7,0 ÷ 25,4	6,7 ÷ 24
α at $K_{\$min}$ [%]	37,8	43,4	41	24,8	23,5	22,2
α at $K_{\$max}$ [%]	24,1	27,7	26,2	15,8	15.1	14,2
Min ÷ Max values of $K_{\$}$ [\$/GJ] − [\$/MWh]	$K_{\$min} = 30$–108 $K_{\$max} = 47$–168		$K_{\$min} = 30$–108 $K_{\$max} = 47$–168		$K_{\$min} = 30$–108 $K_{\$max} = 47$–168	

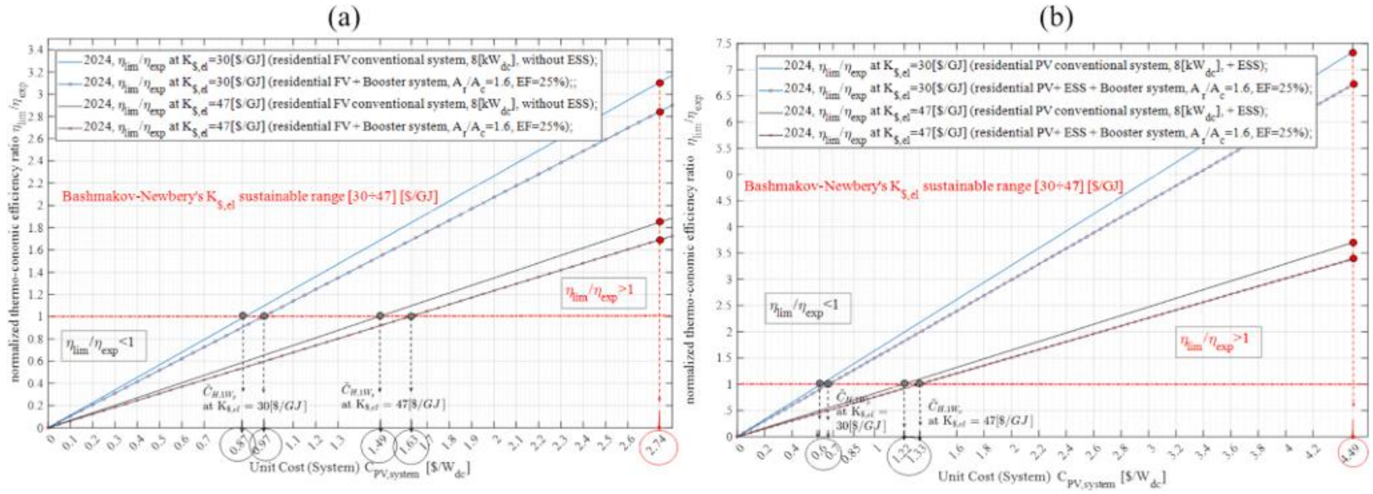

Fig. 4. Residential PV sector without (a) and with (b) ESS, under 2024 MSP long term analysis. Normalized thermo-economic efficiency index η_n, as a function of the unit cost, for conventional and augmented booster reflector collector arrangement.

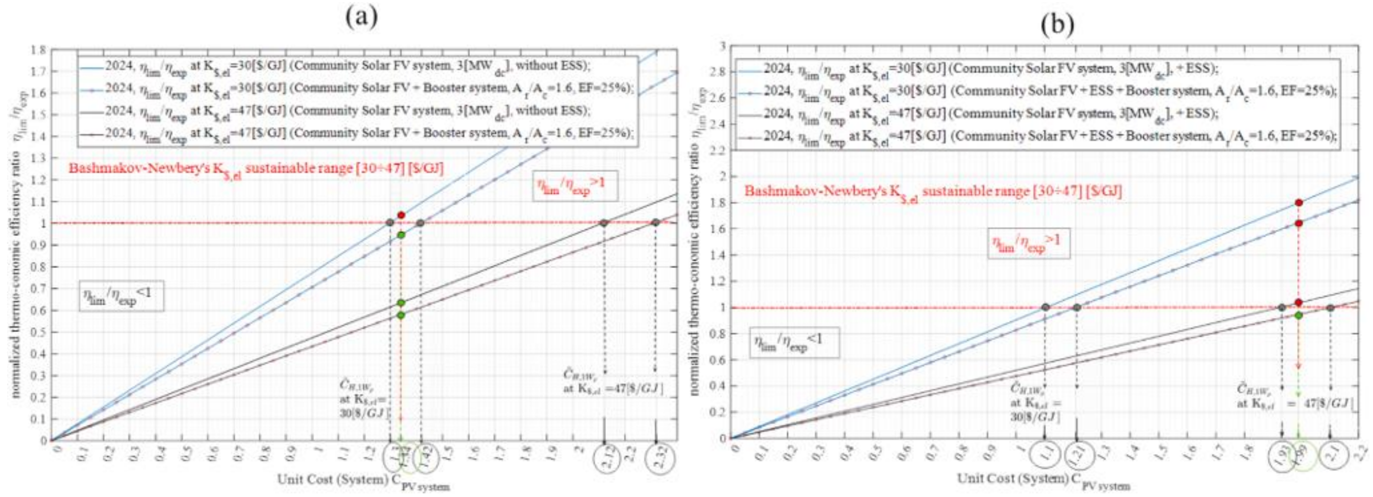

Fig. 5. Solar Community PV sector, without(a) and with (b) ESS, under 2024 MSP long term analysis. Normalized thermo-economic efficiency index η_n, as a function of the unit cost, for conventional and augmented booster reflector collector arrangement.

of community programs with the GES framework. Many jurisdictions credit subscribers at or near retail rates via bill-credit mechanisms, add location-based adders for constrained feeders, and compensate renewable attributes separately. These features increase the private value of delivered kilowatt-hours above the macro-averaged $K_{\$}$ used here, improving developer and subscriber economics even when some configurations sit close to the GES boundary. In our formulation, the average economic value of energy must remain within the affordability band to preserve macro-consistency; private cash flows can be higher if they are offset elsewhere in the system. This distinction clarifies why community PV can expand under supportive crediting while still requiring a check against the long-run affordability constraint. Fig. 5(a) illustrates that at the lower end of the sustainable range (around 30 $/GJ) projects may become marginal, but modest optical augmentation shifts borderline cases back into feasibility.

Including the storage changes the picture as adding a lithium–ion system increases both upfront capex and O&M, steepening the normalized thermos-economic curve. Compliance with the GES appears only near the upper end of the affordability band and remains sensitive to small deviations in resource, cost, or finance parameters. In these PV + ESS cases (Fig. 5(b)), booster reflectors help, chiefly by raising effective yield rather than meaningfully lowering soft-cost burdens, and they can pull select projects just inside the feasible domain at high $K_{\$}$. However, because the feasibility margin is narrow, small cost increases or performance shortfalls can push the system outside GES.

Two practical implications follow. First, the community segment is the natural “sweet spot” for near-term macro-consistent deployment without storage as it captures much of the utility-scale cost structure while avoiding the heavy soft-cost loading that penalizes rooftops. Second, where program rules seek to couple community PV with firming, the macro sustainability gap should be addressed explicitly by targeting sites with superior resource and interconnection conditions, or by driving further cost reductions in storage and soft-cost line items.

3.3. Utility scale sector

At utility scale the normalized thermo-economic index reveals the broadest compatibility with Global Economic Sustainability. Tracking arrays at this size combine disciplined EPC and O&M practices with high specific yield, which places the MSP-based total unit cost well below the critical unit-cost curve across most of the sustainable price band. Under the 2024 MSP, the cost stack shifts upward and the feasibility margin narrows, yet PV without storage remains inside the GES-consistent region over a large sub-range of $K_{\$}$ (Fig. 6).

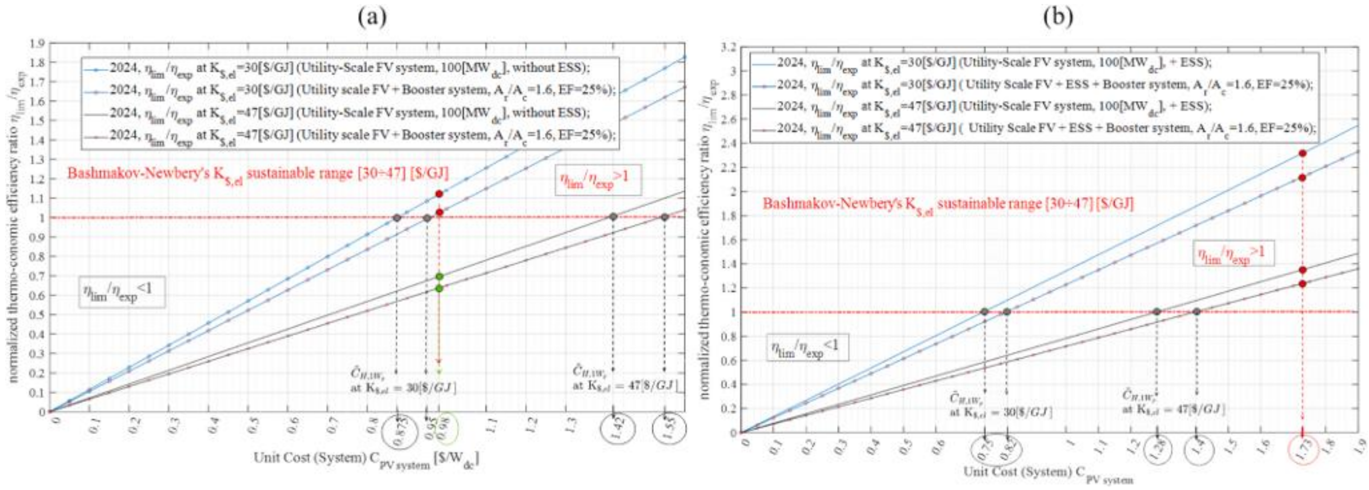

Fig. 6. Utility Scale PV sector, without (a) and with (b) ESS, under 2024 MSP long term analysis. Normalized thermo-economic efficiency index η_n, as a function of the unit cost, for conventional and augmented booster reflector collector arrangement.

The steeper gradient of the utility curves, compared to the community projects, is a direct consequence of the five-year payback horizon. A shorter horizon raises the annualized capital requirement captured by the index, so small movements in either cost or yield translate into larger movements against the $\eta_n = 1$ frontier. This is why feasibility tightens as $K_\$$ approaches the lower end of the band even though the absolute MSP values are the lowest at this scale. The behaviour is financially coherent. Compressing recovery of the capital to five years demands a higher effective efficiency or a lower total unit cost to keep macro affordability intact.

Reflector augmentation increases the available feasibility margin where it is most critical. By increasing effective yield with a modest and well bounded cost adder, reflectors shift the operating point toward the feasible region when K is close to its lower limit. The engineering takeaway is that reflectors are a sensible design lever for low-K or lower-yield sites, but they are not a substitute for cost discipline in EPC and O&M.

Adding storage changes the verdict. The 60 MW / 240 MWh block raises CAPEX and O&M enough to move the PV + ESS operating point above the critical curve for the entire sustainable price range as shown in Fig. 6(a) and (b). The incremental yield from reflectors cannot close this gap because it accrues only to the PV side while storage costs dominate the delta. Within the index this appears as η_n remaining above unity across all $K_\$$, which signals macro-infeasibility rather than a marginal miss.

3.4. Sensitivity analysis

A dedicated sensitivity analysis is performed to assess how variations in key techno-economic parameters influence the feasibility of photovoltaic systems under the Global Economic Sustainability (GES) framework. Two complementary perspectives were examined. The first focuses on extending the operational lifetime of the system beyond the chosen payback period, in order to determine the minimum number of years required for each configuration to enter the GES-compatible region. The second explores the upper limit of the discount rate that preserves economic sustainability, while simultaneously introducing a ± 5 % perturbation in annual solar availability with respect to the reference value. The first part of the analysis investigates how the thermo-economic balance evolves when the number of operational years increases. Since the normalized thermo-economic efficiency decreases with longer lifetime, the boundary between sustainable and unsustainable configurations shifts accordingly. In this study, the operational lifetime was progressively extended up to a maximum of 35 years, corresponding to the typical end-of-life management horizon for commercial PV installations. For each sector and system configuration, the objective is to identify the minimum operational lifetime at which the system becomes compatible with GES requirements, particularly when the electricity price assumes the lower bound of the sustainable range (30 \$/GJ). The results reveal three distinct behaviors across the residential, community, and utility-scale sectors. In the residential sector, the extension of the operational lifetime has a markedly different effect depending on whether storage is included. When only the PV system is considered, increasing the lifetime to the upper limit of 35 years allows the installation to enter the GES-feasible region. This indicates that, despite the structurally high share of soft costs that characterizes small-scale systems, a sufficiently long operating horizon is able to reduce the annualized economic burden to the point where the normalized thermo-economic index falls below unity. When storage is added, however, the situation changes completely. Even when the lifetime is extended to its maximum value, the additional cost associated with the ESS prevents any convergence toward economic sustainability. The community solar sector exhibits a more favorable response. For PV-only systems, extending the operational lifetime to approximately 18 years proves sufficient for full GES compliance. At this threshold, the critical cost associated with the thermo-economic locus lies below the sector's unit cost for all sustainable electricity-price values, including the minimum of 30 \$/GJ. When storage is included, however, the situation becomes more delicate. Only at the maximal lifetime of 35 years do PV + ESS systems with booster reflectors approach sustainability conditions. The conventional PV + ESS configuration, in contrast, remains outside the feasible region, since even at extended lifetimes the normalized thermo-economic efficiency stays above unity. This highlights the role of booster reflectors as a marginal, although not decisive, enhancement mechanism in scenarios where storage costs dominate the economic balance. In the utility-scale sector, the influence of lifetime extension is even stronger. Owing to economies of scale and higher solar resource availability, only eleven years are required for PV-only systems to enter the GES-compatible region. When storage is integrated, the system is not sustainable under the baseline assumptions used in previous sections, which adopt a strict payback time of five years. However, when the operational horizon is extended to 35 years, both conventional and reflector-enhanced PV + ESS configurations fall within the sustainable domain throughout the entire electricity-price range. This demonstrates the strong sensitivity of utility-scale PV + ESS systems to the choice of financial horizon: once the severe constraint of short-term capital recovery is relaxed, the thermo-economic balance becomes more favorable, even in the presence of expensive storage assets. All corresponding figures, constructed in the same form as the efficiency-cost planes used in the main analysis, are reported in Appendix D of the supplementary material (Figs. 1D–6D) for each sector and configuration.

The second part of the sensitivity analysis examines the combined influence of the discount rate and annual solar availability on the feasibility of the different PV configurations. This identifies, for every assumed operational lifetime, the maximum discount rate below which the system remains GES-compliant. In parallel, the annual solar resource was perturbed by + 5 % and − 5 % relative to the reference value, in order to account for variability in local climatic conditions and uncertainties in long-term irradiation estimates. The results are represented in the (n_s, d) plane, where each point corresponds to a specific combination of operational lifetime and discount rate. The thermo-economic model naturally divides this plane into two macro-regions: a lower region in which the system satisfies GES constraints and an upper region in which sustainability is lost. For both bounds of the sustainable electricity-price range, four curves included in the (n_s, d) plane: two for solar availability and its ± 5 % variations for conventional systems, and two curves for reflector-enhanced configurations. Across all sectors, the analysis reveals a consistent trend, as shown in Figs. 7, 8, and 9. As expected, longer operational horizons allow progressively higher discount rates while preserving GES compliance. For a fixed lifetime, utility-scale systems (Fig. 9) exhibit the largest sustainable zone in the (n_s, d) plane, reflecting their favorable cost structure and higher energy yields. Community-scale (Fig. 8) installations occupy an intermediate position, while residential systems (Fig. 7) display only a narrow sustainable region, in agreement with the baseline results discussed earlier. When the discount rate is fixed at 4 %, one recovers precisely the same lifetime thresholds, previously identified for each sector, is clearly obtained, confirming the consistency of the model. Introducing the energy storage substantially reduces the size of the GES-feasible region, as it visible from Figs. 7, 8 and 9(b). In the residential sector, the area of sustainability becomes an extremely thin strip, observable only at the upper bound of the sustainable electricity-price range. The community sector also displays a contraction of the feasible region, though booster reflectors help maintain sustainability near the highest electricity-price values. The utility-scale sector shows greater resilience, but even here the inclusion of storage narrows the feasible region and increases the sensitivity of the design to small reductions in solar availability.

Overall, the sensitivity analysis indicates that GES compliance is primarily governed by the operational lifetime and discount rate across all sectors, with utility-scale systems showing the widest tolerance to higher discount rates and shorter lifetimes. Community-scale systems exhibit an intermediate between the utility scale and the residential sector. The latter remains highly constrained, especially when storage is included. Variations in solar availability play a secondary but non-negligible role, mainly affecting designs including the presence of the storage.

4. Conclusions

This study frames photovoltaic feasibility through the perspective of Global Economic Sustainability, which incorporates long-term empirical evidence on the sustainable share of income devoted to energy that supports economic growth. According to the first Bashmakov–Newbery law of energy transition, sustained exceedance of affordability thresholds is commonly associated with an elevated risk of economic downturn, adversely affecting typical economies.

The present analysis translates this evidence into a sustainable range for electricity and primary energy unit prices, together with an upper affordability limit. An analytical relationship between the Bashmakov–Newbery range and the sustainable unit energy price $K_\$$ is derived and supported by long-term global data on Gross Domestic Product, energy intensity, and primary energy use. The study identifies a narrow sustainable energy price corridor gravitating around 94 ± 20 $/BOE for primary energy and 38 ± 8 $/GJ for electrical energy.

To assess the viability of commercial photovoltaic technology within these boundaries, thermodynamic and economic principles are properly linked into a normalized thermo-economic energy conversion efficiency index. This index is implemented within a simulation framework to identify domains of thermo-economic feasibility in which photovoltaic installations can be manufactured, installed, operated, and maintained in accordance with Global Economic Sustainability requirements.

By incorporating trajectories of capital, technological, and O&M costs together with energy performance under different operating conditions, the model sets the Global Economic Sustainability threshold for commercial photovoltaic technologies across residential, community solar, and utility-scale sectors, considering configurations with and without energy storage systems. The contribution of low-cost technological improvements to Global Economic Sustainability (GES) was investigated experimentally by analyzing optimal booster reflector-augmented collector configurations. Concrete photovoltaic configurations were evaluated using recent cost benchmarks and measured resource data. Assumptions, system boundaries, and units were explicitly defined.

Key findings can be summarized as follows.

- Large-scale photovoltaic sectors can follow a fully unsubsidized pathway for scaled-up manufacturing, using labor paid at fair market

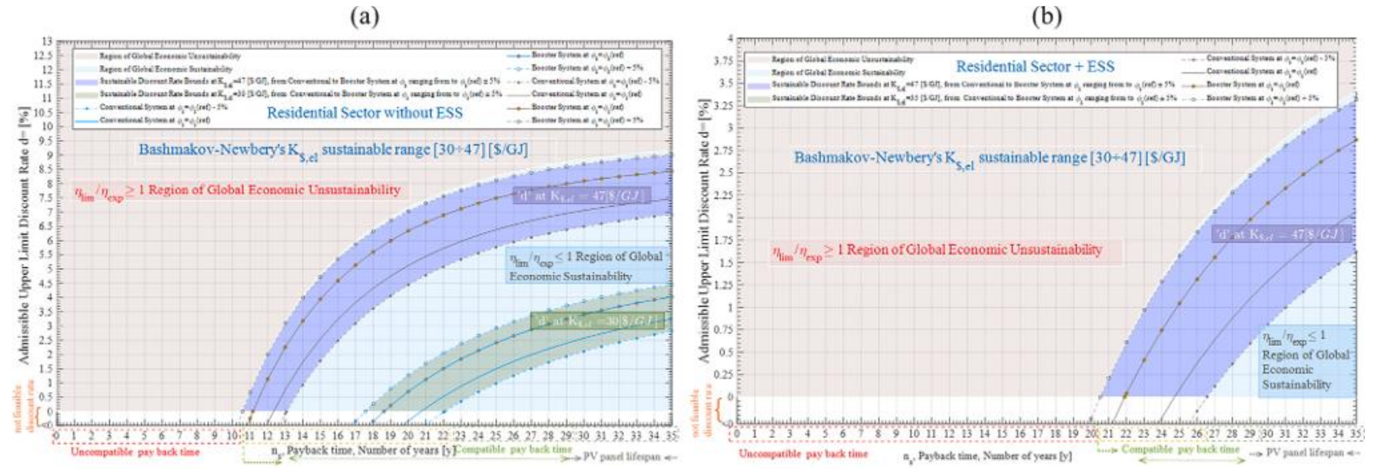

Fig. 7. Sensitivity analysis by varying the number of years to obtain the upper limit of the discount rate, residential sector without storage (a) and with storage (b) with a variation of solar source of ± 5 %.

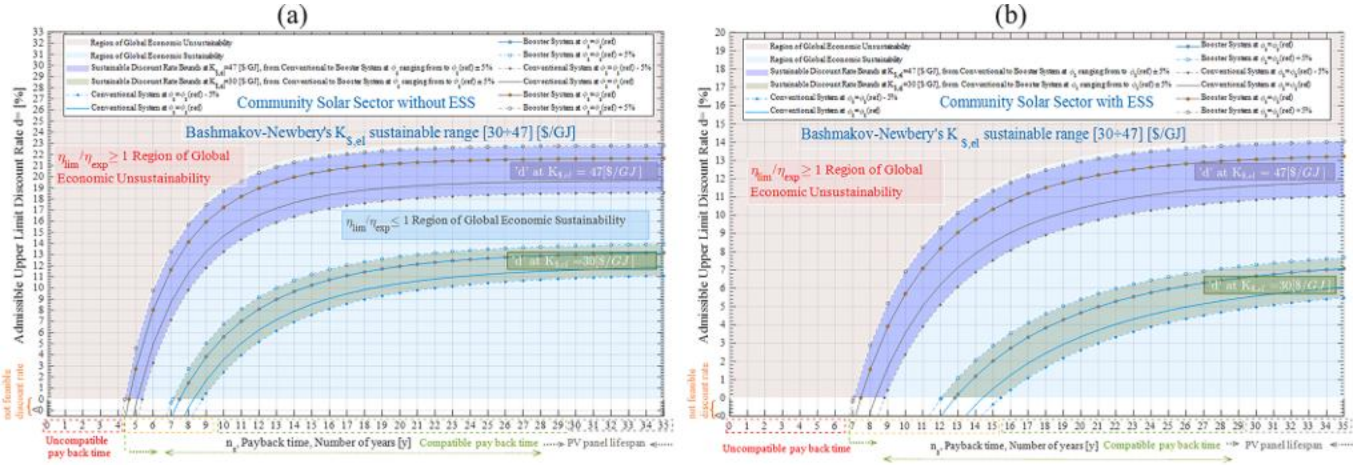

Fig. 8. Sensitivity analysis by varying the number of years to obtain the upper limit of the discount rate. Solar-community sector without storage (a) and with storage (b), with a variation of solar source of ± 5 %.

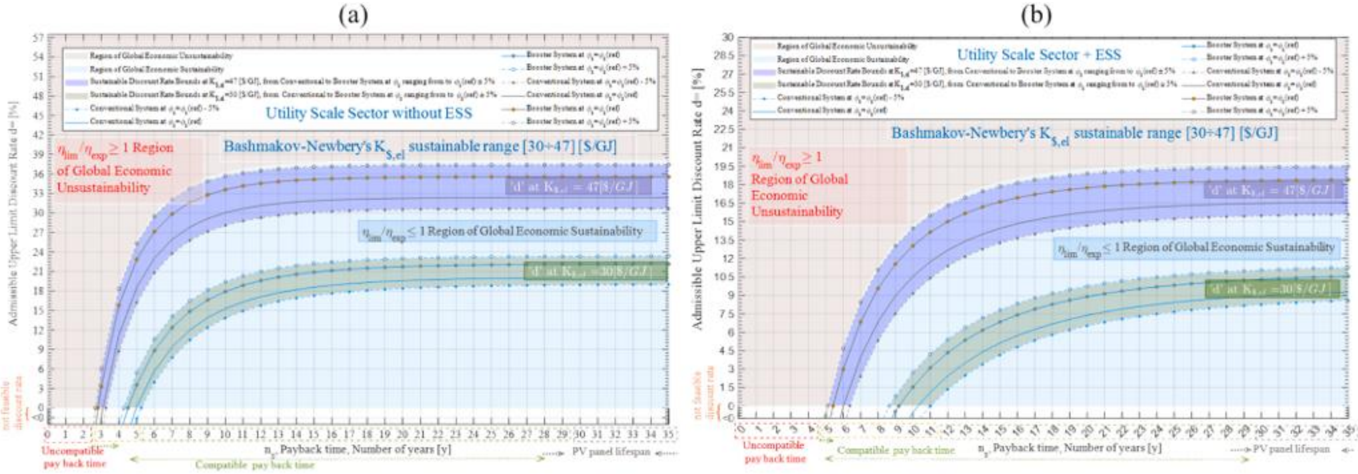

Fig. 9. Sensitivity analysis by varying the number of years to obtain the upper limit of the discount rate. Utility-scale sector without storage (a) and with storage (b).

wages, to deliver end-user energy that satisfies GES requirements, even before the end of their operational lifetime.

- When energy storage is included, affordability costs approach their critical threshold, and photovoltaics with storage configurations in both community and utility-scale sectors fail the GES test unless favorable long-term cost and financial projections are assumed.
- Booster reflectors can marginally restore community and utility-scale projects to the sustainable range of energy expenditure; however, even small deviations from optimal economic or financial conditions, or from key energy explanatory variables, may attract the solar projects outside the Bashmakov–Newbery region.
- The residential sector exhibits the most critical scenario, even over the full lifetime horizon, as its cost structure is dominated by preponderant soft costs (approximately 62 % of the total), placing its critical cost entirely outside the GES range. Reflector augmentation provides only modest performance gains.

The analysis developed here is not prescriptive and should not be interpreted as a definitive assessment of photovoltaic technology. Rather, it provides a robust analytical framework to support planners and regulators in assessment and scenario development concerning the future role attributed to commercial photovoltaic technologies within the broader energy transition. The framework complements levelized cost metrics by highlighting combinations of cost structure, resource availability, and financing conditions consistent with Global Economic Sustainability.

Future research should embed the proposed index in time-resolved power system models, explicitly accounting for environmental externalities and supply-chain risks, calibrate sustainable energy prices by country and sector, and test robustness under policy changes and cost volatility.

To situate these results within the current technological context, it should be noted that decades of investment have made mono-junction crystalline silicon photovoltaics reliable and cost-effective, but their efficiency is now approaching practical limits, leaving limited room for further improvement. However, the urgency of climate change demands faster and more affordable scale-up pathways beyond sustained reliance on subsidized installations. Third-generation technologies—including organic, heterojunction, and perovskite solar cells—show potential for large-scale adoption driven by higher learning rates, but remain in early industrialization stages, where both risks and opportunities coexist.

As global temperatures approach the 1.5 °C threshold, Humanity's ability to choose whether to harness the radiation from the Sun's natural nuclear reactions or be forced to rely on artificial reactions within our own reactors will depend on the success of our endeavors to fully exploit all the mechanisms offered by solar energy.

CRediT authorship contribution statement

Armando Di Meglio: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Fanti:** Writing – review & editing, Writing – original draft, Conceptualization. **Gianluca Gatto:** Writing – review & editing, Writing – original draft, Conceptualization. **Amit Kumar:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Matteo Lodi:** Writing – review & editing, Writing – original draft, Conceptualization. **Raffaello Possidente:** Writing – review & editing, Writing – original draft, Conceptualization. **Roberto Baccoli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2026.121202.

Data availability

Data will be made available on request.

References

[1] Newbery DM. Sectoral dimensions of sustainable development: energy and transport. Econ Surv Eur 2003:73–100.

[2] Bashmakov I, Myshak A. “Minus 1” and energy costs constants: sectorial implications. J Energy 2018;2018:8962437.

[3] Bashmakov I. The first law of energy transitions and carbon pricing. Int J Energy, Environ Econ 2017;25:1–42.

[4] Bashmakov I. Energy consumption and economic growth: factors and limits of proportions changes. Moscow: Energetica Aktualnye Problemy International Center of Scientific and Technical Information; 1988. p. 50–61.

[5] Bashmakov I, Grubb M, Drummond P, Lowe R, Myshak A, Hinder B. 'Minus 1'and energy costs constants: empirical evidence. Theory and Policy Implications: Theory and Policy Implications; 2023.

[6] Grubb M, Bashmakov I, Drummond P, Myshak A, Hughes N, Biancardi A, et al. An exploration of energy cost, ranges, limits and adjustment process. UCL-ISR 2018.

[7] Agnolucci P, De Lipsis V, Gencer D, Lartey A, Grubb M. The evolution and implications of national energy cost shares. Energy Econ 2025:108616.

[8] Rühle S. Tabulated values of the shockley–queisser limit for single junction solar cells. Sol Energy 2016;130:139–47.

[9] Pourasl HH, Barenji RV, Khojastehnezhad VM. Solar energy status in the world: a comprehensive review. Energy Rep 2023;10:3474–93.

[10] IEA-PVPS. Snapshot of Global PV Markets 2025 Task 1 Strategic PV Analysis and Outreach PVPS. n.d.

[11] IRENA. Renewable capacity statistics 2024 STATISTIQUES DE CAPACITÉ RENOUVELABLE 2024 ESTADÍSTICAS DE CAPACIDAD RENOVABLE 2024 About IRENA. 2024.

[12] Chen Z, Gu B, Yu D, Wang C. Quantifying the accelerated diffusion and cost savings of global solar photovoltaic supply chains. IScience 2025;28.

[13] Shah AUI, Meyer EL. Perovskite-based solar cells in photovoltaics for commercial scalability: current progress, challenges, mitigations and future prospectus. Sol Energy 2025;286:113172.

[14] Padture NP, Berry JJ, Unger E. Halide perovskite solar photovoltaics. MRS Bull 2024;49:1235–9.

[15] Song T, Jeswani HK, Azapagic A. Assessing the environmental and economic sustainability of emerging tandem photovoltaic technologies in China. Energy Convers Manag 2024;318:118890.

[16] Zhang L, Wang Y, Meng X, Zhang J, Wu P, Wang M, et al. The issues on the commercialization of perovskite solar cells. Mater Futures 2024;3.

[17] Muteri V, Cellura M, Curto D, Franzitta V, Longo S, Mistretta M, et al. Review on Life Cycle Assessment of Solar Photovoltaic Panels. Energies 2020, Vol 13, Page 252 2020;13:252. DOI: 10.3390/EN13010252.

[18] Victoria M, Haegel N, Peters IM, Sinton R, Jäger-Waldau A, Del Cañizo C, et al. Solar photovoltaics is ready to power a sustainable future. Joule 2021;5:1041–56.

[19] Martinez-Val JM. Energy for Sustainable development: a systematic approach for a badly defined challenge. Energy Convers Manag 2013;72:3–11.

[20] Alex-Oke T, Bamisile O, Cai D, Adun H, Ukwuoma CC, Tenebe SA, et al. Renewable energy market in Africa: opportunities, progress, challenges, and future prospects. Energ Strat Rev 2025;59:101700.

[21] Cerchione R, Morelli M, Passaro R, Quinto I. Balancing sustainability and circular justice: the challenge of the energy transition. J Clean Prod 2025;494:144942. https://doi.org/10.1016/J.JCLEPRO.2025.144942.

[22] Ghadim HV, Haas J, Breyer C, Gils HC, Read EG, Xiao M, et al. Are we too pessimistic? Cost projections for solar photovoltaics, wind power, and batteries are over-estimating actual costs globally. Appl Energy 2025;390:125856.

[23] Ramasamy V, Zuboy J, Feldman D, Margolis R, Desai J, Walker H. Q1 2023 us solar photovoltaic system and energy storage cost benchmarks with minimum sustainable price analysis data file. 2023.

[24] U.S. Department of Energy (DOE) Solar Energy Technologies Office. Solar Photovoltaic System Cost Benchmarks, n.d.

[25] Braff WA, Mueller JM, Trancik JE. Value of storage technologies for wind and solar energy. Nat Clim Chang 2016;6:964–9.

[26] Rana MM, Uddin M, Sarkar MR, Shafiullah GM, Mo H, Atef M. A review on hybrid photovoltaic–battery energy storage system: current status, challenges, and future directions. J Energy Storage 2022;51:104597.

[27] Patel J, Patel AR. Numerical investigation on the effect of different types of configuration on the optical performance of solar flat plat reflecting system. Sustainable Energy Technol Assess 2024;61:103586.

[28] Gelegenis JJ, Axaopoulos P, Misailidis S, Giannakidis G, Samarakou M, Bonaros B. Feasibility for the use of flat booster reflectors in various photovoltaic installations. Int J Renew Energy Res 2015;5:82–98.

[29] Rönnelid M, Karlsson B, Krohn P, Wennerberg J. Booster reflectors for PV modules in Sweden. Prog Photovolt Res Appl 2000;8:279–91.

[30] Hess S. Stationary booster reflectors for solar thermal process heat generation, 2015.

[31] Baccoli R, Kumar A, Frattolillo A, Mastino C, Ghiani E, Gatto G. Enhancing energy production in a PV collector–reflector system supervised by an optimization model: experimental analysis and validation. Energy Convers Manag 2021;229:113774.

[32] Baccoli R, Frattolillo A, Mastino C, Curreli S, Ghiani E. A comprehensive optimization model for flat solar collector coupled with a flat booster bottom reflector based on an exact finite length simulation model. Energy Convers Manag 2018;164:482–507.

[33] Baccoli R, Mastino CC, Innamorati R, Serra L, Curreli S, Ghiani E, et al. A mathematical model of a solar collector augmented by a flat plate above reflector: optimum inclination of collector and reflector. Energy Procedia 2015;81:205–14.

[34] Breyer C, Khalili S, Bogdanov D, Ram M, Oyewo AS, Aghahosseini A, et al. On the history and future of 100% renewable energy systems research. IEEE Access 2022;10:78176–218.

[35] Rahman MM, Oni AO, Gemechu E, Kumar A. Assessment of energy storage technologies: a review. Energy Convers Manag 2020;223:113295.

[36] Bashmakov I. Three laws of energy transitions and economic growth. Energy Effic 2025;18:7.

[37] Fizaine F, Court V. Energy expenditure, economic growth, and the minimum EROI of society. Energy Policy 2016;95:172–86.

[38] Bashmakov I. Three laws of energy transitions. Energy Policy 2007;35:3583–94.

[39] Blakesley JC, Bonilla RS, Freitag M, Ganose AM, Gasparini N, Kaienburg P, et al. Roadmap on established and emerging photovoltaics for sustainable energy conversion. J Phys: Energy 2024;6:41501.

[40] Kirchartz T, Yan G, Yuan Y, Patel BK, Cahen D, Nayak PK. The state of the art in photovoltaic materials and device research. Nat Rev Mater 2025:1–20.

[41] Durković V, Urišić Ž. Efficiency increase analysis of large RFPV power plants using reflectors between PV rows. J Renewable Sustainable Energy 2020;12.

[42] Sánchez A, Zhang Q, Mart'ın M, Vega P. Towards a new renewable power system using energy storage: an economic and social analysis. Energy Convers Manag 2022;252:115056.

[43] McFarland EW. Solar energy: setting the economic bar from the top-down. Energy Environ Sci 2014;7:846–54.

[44] Praveenkumar S, Kumar A. Thermodynamic, environmental and economic analysis of solar photovoltaic panels using aluminium reflectors and latent heat storage units: an experimental investigation using passive cooling approach. J Energy Storage 2025;112:115487.

[45] Sultan SM, Abdullah MZ, Tso CP, Abllah NFN, Zakaria N, Ajeel RK, et al. An economic feasibility assessment of implementing photovoltaic module reflectors under Malaysian meteorological conditions. Sci Rep 2024;14:3349.

[46] PraveenKumar S, Agyekum EB, Kumar A, Velkin VI. Performance evaluation with low-cost aluminum reflectors and phase change material integrated to solar PV modules using natural air convection: an experimental investigation. Energy 2023;266:126415.

[47] Rachedi MY, Bechki D, Marif Y, Boughali S, Bouguettaia H. A novel model for optimizing tilts of four reflectors on a flat plate thermal collector: case study in Ouargla region. Case Stud Therm Eng 2022;32:101872.

[48] Durković V, Urišić Ž. Impact of a horizontal reflector on the techno-economic characteristics of large VPV power plants. Sol Energy 2021;220:650–9.

[49] Simon SP, Kumar KA, Sundareswaran K, Nayak PSR, Padhy NP, et al. Impact and economic assessment on solar PV mirroring system–a feasibility report. Energy Convers Manag 2020;203:112222.

[50] Nour CA, Migan-Dubois A, Badosa J, Bourdin V, Marchand C, Akiki T. Geometrical optimization for a photovoltaic installation equipped with flat reflectors based on plane of array estimations. EPJ Photovoltaics 2020;11:1.

[51] Auti AB, Pangavane DR, Singh TP, Sapre M, Warke AS. Study on reflector material optimization of a parabolic solar concentrator. Power Electronics and Renewable Energy Systems: Proceedings of ICPERES 2014, Springer; 2014, p. 275–84.

[52] Kabeel AE, Abdelgaied M, Sathyamurthy R. A comprehensive investigation of the optimization cooling technique for improving the performance of PV module with reflectors under Egyptian conditions. Sol Energy 2019;186:257–63.

[53] Huang BJ, Sun FS. Feasibility study of one axis three positions tracking solar PV with low concentration ratio reflector. Energy Convers Manag 2007;48:1273–80.

[54] Ahmad GE, Hussein HMS. Comparative study of PV modules with and without a tilted plane reflector. Energy Convers Manag 2001;42:1327–33.

[55] Hamed A, Al-Ghussain L, Hassan MA, Annuk A. Techno-economic analysis for optimal configurations of PV systems with back reflectors. Energy Rep 2022;8:14979–96.

[56] Gonzalez MAO, Urbiola EAC, Garcia FL, Ramirez MV, Hernandez DF, Reyes GU, et al. Innovations in solar energy: synthesis and evaluation of diffuse booster reflector ceramic coating for enhancing thermal and photovoltaic systems performance. Energy Rep 2024;12:2224–31.

[57] Rasheed Otman A, Awami AH, Hamad T. Performance analysis of PV solar panels augmented by plane reflectors in elbida-libya: an experimental study. Sol Energy Sustain Dev J 2025;14:55–72. https://doi.org/10.51646/jsesd.v14iFICTS-2024.443.

[58] Qiu G, Wang Y, Chen Y, Cai W. Study on the performance of flat-plate collectors with a bottom-mounted non-tracking broken line type reflector. Renew Energy 2024;237:121644.

[59] Ardiyanto ED, Arifin Z, Rachmanto RA, Basyar K, Prasetyo SD. Amplification of solar radiation intensity on photovoltaic panel using reflectors to increase power output. Int Conf Exhib Sustainable Energy Adv Mater 2023:285–95.

[60] Ardiyanto ED, Arifin Z, Rachmanto RA. The experimental study of photovoltaic performance improvement using multiple reflectors. Int J Energy Convers 2023;11.

[61] Rachedi MY, Bechki D, Bouguettaia H. Photovoltaic module augmented by commercial reflectors in southern Algeria: comparison between different reflective materials. Acta IMEKO 2023;12:1–6.

[62] Agrawal M, Chhajed P, Chowdhury A. Performance analysis of photovoltaic module with reflector: optimizing orientation with different tilt scenarios. Renew Energy 2022;186:10–25.

[63] Benkaddour A, Boulaich H, Aroudam E. Comparative study of electricity production by photovoltaic Panels with mirrors for different inclinations. In: WITS 2020: Proceedings of the 6th International Conference on Wireless Technologies, Embedded, and Intelligent Systems; 2021. p. 749–57.

[64] Suyitno BM, La Ode MF, Augupta E. Analysis of solar power plants with the combination systems of PV module-reflective mirror. WSEAS Trans Syst Control 2022;17:167–76.

[65] Sharma A, Bajpai VK. Enhancement of power generation efficiency of PV system using mirror reflector. Int J Ambient Energy 2022;43:8036–45.

[66] Palaskar VN, Deshmukh SP, Pandit AB. Design and performance analysis of reflectors attached to commercial PV module. Int J Renewable Energy Res 2014;4:240–5.

[67] Bashmakov I, Grubb M, Drummond P, Lowe R, Myshak A, Hinder B. “Minus 1” and energy costs constants: empirical evidence, theory and policy implications. Struct Chang Econ Dyn 2024;71:95–115. https://doi.org/10.1016/J.STRUECO.2024.06.010.

[68] Bashmakov I. “Economics of the constants” and long cycles of energy prices dynamics. Vopr Ekon 2016.