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IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Date of publication xxxx 00, 2025, date of current version xxxx 00, 2025.

Digital Object Identifier xxx/ACCESS.2025.DOI

Hybrid Renewable Energy Systems in Türkiye: A Multi-Scenario Assessment of Demand, Metering, and Carbon Tax Policies

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ABSTRACT The accelerating demand for low-carbon energy solutions highlights the critical role of hybrid renewable energy systems (HRES) in achieving decarbonization, energy security, and economic resilience. This study offers a comprehensive techno-economic and environmental evaluation of HRES integrating photovoltaic, wind, and battery storage technologies across Türkiye's diverse climatic regions and sectoral demand profiles (residential, commercial, industrial). Utilizing 48 scenario-based simulations via HOMER Pro, the analysis incorporates real-world policy instruments including carbon taxation, net metering (NM), and net billing (NB). A novel sensitivity analysis reveals that under NB, battery integration becomes economically viable at carbon prices above 40–50 \$/tCO_2, while NM lowers this threshold to around 20 \$/tCO_2. Additionally, a 40 \$/tCO_2 carbon tax increases the renewable energy fraction by 32% and reduces the levelized cost of energy (LCOE) by 11.75%. Commercial users in wind-rich regions benefit most under NM, achieving up to 22% lower net present cost (NPC). While NM maximizes renewable deployment and short-term returns, NB ensures greater economic discipline and supports battery investments under high tariff and carbon scenarios. Expanded performance indicators, including self-supply rate, self-consumption rate, and energy exchange rate, provide operational insights beyond conventional metrics. The findings offer region-specific and policy-aware recommendations, suggesting that hybrid models combining NM and NB, supported by moderate carbon pricing and targeted incentives, can optimize system performance while ensuring affordability and equity in Türkiye's energy transition. This framework offers strategic guidance for regulators, investors, and planners in emerging economies.

INDEX TERMS Carbon Tax, Economic Policies, Hybrid Renewable Energy Systems, Net Metering, Net Billing, Techno-Economic Analysis, Incentive Mechanisms, Optimization

I. INTRODUCTION

In the context of contemporary energy transition, climate change, and sustainable development goals, the integration of renewable energy sources has gained significant importance. Hybrid renewable energy systems (HRES), which combine different renewable sources such as solar and wind, offer effective solutions to enhance energy supply security and reduce carbon emissions. However, the performance and economic feasibility of these systems vary significantly depending on a wide range of factors, including geographical conditions, consumer profiles, and local energy policies. Particularly in countries like Türkiye, where renewable energy potential is high but regional and sectoral disparities are prominent, there is a growing need for comprehensive and policy-oriented approaches to the design and optimization of hybrid energy systems. In this context, considering the diversity of renewable energy resources such as solar irradiation and wind speed across different cities, along with the

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Nomenclature	Definition	Abbreviation	Definition
P_{PV}^{t}	Actual output power of PV system (kW)	HRES	Hybrid renewable energy systems
$P_{\mathrm{PV}}^{\mathrm{STC}}$	Nominal capacity of PV panel at STC (kW)	NPC	Net present cost ($)
f_{PV}	Derating factor of the PV panel	PSO	Particle swarm optimization
$\mathrm{IR}_{\mathrm{PV}}^{t}$	Solar radiation under operational cond. (W/m²)	SLB	Second-life battery
$\mathrm{IR}_{\mathrm{PV}}^{\mathrm{stc}}$	Solar radiation at STC (W/m²)	GWO	Grey wolf optimization
α_P	Temperature coeff. of panel power (1/°C)	PV	Photovoltaic panel
T_C^t	PV cell temperature (°C)	CE	Clipped or curtailed energy
T_C^{stc}	Cell temperature at STC (°C)	RES	Renewable energy sources
$\eta_{\mathrm{mp}}^{\mathrm{stc}}$	Max efficiency under STC (%)	GDP	Gross domestic product
A_{PV}	Panel area (m²)	WT	Wind turbine
T_a^t	Ambient temp. during operation (°C)	FiT	Feed-in tariffs
T_C^{NOCT}	Nominal operating cell temp. (°C)	NPV	Net present value
T_a^{NOCT}	Ambient temp. at NOCT (°C)	SCR	Self-consumption ratio (%)
G_T^t	Solar radiation incident on PV (W/m²)	SSR	Self-supply rate (%)
G_T^{NOCT}	Solar radiation level at NOCT (W/m²)	LCOE	Levelized cost of energy ($/kWh)
τ	Solar transmittance of covering	EXR	Energy exchange rate (%)
α	Solar absorptance of PV array	HPS	Hybrid power system
U_{hub}	Wind speed at hub height (m/s)	DF	Derating factor
U_{anem}	Wind speed at anemometer (m/s)	STC	Standard test conditions
H_{hub}	Hub height of wind turbine (m)	NOCT	Nominal operating cell temperature
H_0	Surface roughness length (m)	DoD	Depth of discharge (%)
H_{anem}	Height of anemometer (m)	SoC	State of charge (%)
P^{WT}	Output power of wind turbine (kW)	ASM	Advanced storage model
$P_{\mathrm{STP}}^{\mathrm{WT}}$	Turbine power at STC (kW)	ESS	Energy storage system
ρ	Actual air density (kg/m³)	PCS	Power conversion system
ρ^0	Air density at STP (kg/m³)	EPDK	Energy Market Regulatory Authority
$\mathrm{SoE}_t^{\mathrm{ESS}}$	Energy state at time t (kWh)	ToU	Time-of-use
$\mathrm{SoE}_{t-1}^{\mathrm{ESS}}$	Energy state at time t-1 (kWh)	SOH	State of health (%)
$P_t^{\mathrm{ESS}_{\mathrm{chr}}}$	Charging power of ESS (kW)	EoL	End of battery life
η_{chr}	Charging efficiency (%)	YEKDEM	Renewable support mechanism
η_{disch}	Discharging efficiency (%)	VAT	Value added tax
$P_t^{\mathrm{ESS}_{\mathrm{disch}}}$	Discharging power (kW)	IRR	Internal rate of return (%)
$\mathrm{SoE}_{\mathrm{max}}^{\mathrm{ESS}}$	Max energy state (kWh)	DNI	Direct normal irradiance
$\mathrm{SoE}_{\mathrm{min}}^{\mathrm{ESS}}$	Min energy state (kWh)	DHI	Diffuse horizontal irradiance
$P_{\mathrm{out}}^{\mathrm{ESS}}$	Output power of ESS (kW)	GTI	Global tilted irradiance
V_0	Nominal voltage of ESS (V)	DR	Discount rate (%)
I	ESS current (A)	GP	Grid purchase
$I_{P_{\mathrm{out}}}^{\mathrm{max}}$	Max output current (A)	GS	Grid sale
R_0	Series resistance of ESS (Ω)	RF	Renewable fraction (%)
η_{rec}	The rectifier mode efficiency (%)	COE	Cost of energy ($/kWh)
$C_{T_{\mathrm{avail}}}^{\mathrm{ESS}}$	Available temp.-based ESS energy (kWh)	SP	Simple payback period (yr)
$C_{T_{\mathrm{nom}}}^{\mathrm{ESS}}$	ESS capacity at nominal temp. (kWh)	DP	Discounted payback period (yr)
d_0, d_1, d_2	ESS curve param. vs temp. (1/°C)	CT	Carbon tax
T	Ambient temperature (°C)	$\mathrm{Cap}_{\mathrm{PV}}$	Installed PV capacity (kW)
t	Time (hr)	$\mathrm{Cap}_{\mathrm{WT}}$	Installed WT capacity (kW)
A	DoD factor	$\mathrm{Cap}_{\mathrm{ESS}}$	ESS capacity (kWh)
DoD^{β}	DoD exponent	$\mathrm{Cap}_{\mathrm{PCS}}$	PCS capacity (kW)
n, N	Project year	NM	Net metering
D_i	DoD in i-th cycle (%)	NB	Net billing
β	Degradation curvature coeff.	HESS	Hybrid energy storage system

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Nomenclature	Definition	Nomenclature	Definition
D	Exponential battery degradation coefficient.	C_{rep}	The average annual replacement cost ($).
k_t	Temperature-dependent coefficient (e.g., efficiency, rate, degradation factor, etc.).	C_{tax}	The total carbon tax ($).
B	Nominal coefficient at 0°C	CO_2^{tax}	The carbon tax ($/t$CO_2$).
d	Temperature sensitivity coefficient (1/°C)	λ	The CO_2 coefficient for electricity purchase (tCO_2/kWh).
$P^{ESS}_{c_{max,kbm}}$	Kinetic battery model for max. discharge power (kW).	E^t_{GP}	Electricity purchased from the grid (kWh).
$P^{ESS}_{c_{max,mcr}}$	Maximum charge C-rate (kW).	TCO_2	Annual carbon emission (kg).
$P^{ESS}_{c_{max,mcc}}$	Max charging current of energy storage (kW).	E^t_{GS}	Electricity sold to the grid (kWh).
$P^{ESS}_{c_{max}}$	Max charging power under all constraints (kW).	C_{GP}	Total cost of purchasing electricity ($).
$P^{ESS}_{d_{max,kbm}}$	Max discharge power per operation period (kW).	C_{GS}	Revenue from selling electricity ($).
k	Storage rate constant (1/hr).	C^t_{purch}	Cost of purchased electricity ($).
Q^{ESS}_{avail}	Available energy in storage (kWh).	C^t_{sell}	Revenue from sold electricity ($).
Δt	Duration of each time step (hr).	C_{inv}	Initial investment cost ($).
Q^{ESS}_{init}	Initial energy stored in ESS (kWh).	C_{main}	Total maintenance cost ($).
c	Ratio of storage capacity.	C^{tot}_{ann}	Annual hybrid system cost ($/yr).
α_C	Max charge rate of storage (1/hr).	P_{GP}	Grid purchase power (kW).
Q^{ESS}_{max}	Total energy capacity of storage (kWh).	P_{load}, P_L	Load or demand (kW).
N_{bat}	Total number of storage batteries.	P_{PV}	PV power production (kW).
I_{max}	Peak battery charging current (A).	P_F	PV minus battery + load demand at time t (kW).
η^{ESS}_{rt}	Round-trip battery efficiency (%).	P_G	Load demand minus PV + battery power at time t (kW).
P^t_{inv}	Converter output in inverter mode (kW).	$E^{\text{with HPS}}$	Energy supplied with hybrid system (kWh).
P^t_{rec}	Converter output in rectifier mode (kW).	$E^{\text{only grid}}$	Energy supplied without hybrid system (kWh).
η_{inv}	Inverter mode efficiency (%).	$P_{curtailment}$	Unused renewable energy (kW).
P^t_{AC}	AC output power at time t (kW).	SSF(i, N_{comp})	Sinking fund coeff. (based on rate + component life).
P^t_{DC}	DC output power at time t (kW).	N_{comp}	Service life of each HPS component (yr).
i	Real interest rate (%).	f_{RC}	Scale factors.
i'	Nominal interest rate (%).	CRF(i, N_{RC})	Capital recovery factor (real rate, remaining life).
f	Inflation rate (%).	N_{RC}	Remaining component life before replacement (yr).
CRF(i,N)	Capital recovery factor (real rate + year).	N_{rem}	Remaining service life of components (yr).
l	Hybrid power system components.	N_{rep}	Replacement service life of components (yr).
IC^l	Investment cost of each component ($/kW or $/kWh).	C^{tot}_{cap}	Total installed capital cost ($).
C^l_{cap}	Capacity of each HPS component (kW or kWh).	ε	Maintenance factor for HPS (%).
INT$\left(\frac{N}{N_{comp}}\right)$	Integer division of project year and component life.	SSF(i, N)	Sinking fund coefficients (rate and year).

variation in residential, commercial, and industrial consumer groups, emerges as a critical requirement. Moreover, systematically analyzing the impact of incentive mechanisms such as carbon tax, net metering, and net billing on performance and cost-effectiveness could provide valuable insights for policymakers and investors.

This study examines three key instruments, carbon taxation policies, advanced metering infrastructure (AMI), and regional demand profiling, that are frequently cited in the literature as influential tools for sustainable energy system planning and investment. The selection of these instruments is grounded in their demonstrated impact on two critical objectives: enhancing grid efficiency and supporting carbon neutrality goals. Carbon taxes have been widely implemented as market-based mechanisms to reduce greenhouse gas emissions by internalizing externalities and shifting investments towards cleaner technologies [1]. Advanced metering infrastructure contributes to grid optimization by enabling demand-side flexibility, improving real-time monitoring, and facilitating the integration of distributed renewable sources [2]. Additionally, regional demand profiling, when combined with geographic diversity analysis, allows for the design of

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tailored hybrid renewable energy systems (HRES) that align with local consumption patterns and renewable resource availability [3]. By focusing on these three instruments, the study provides a comprehensive assessment framework that bridges economic, technical, and policy dimensions, specifically within the context of Türkiye's evolving energy landscape.

Building on the importance of policy-oriented approaches and incentive mechanisms discussed above, recent studies have increasingly focused on the combined effectiveness of market-based instruments such as carbon taxes with direct supportive policies including renewable energy investments (REI) and renewable portfolio standards (RPS) in driving a successful low-carbon energy transition. For instance, integrated model analyses developed in [4] suggest that implementing a carbon tax alone may lead to economic losses; however, when complemented by REI, environmental benefits can be maximized while mitigating economic drawbacks. Similarly, [5] demonstrates that the joint implementation of RPS and carbon tax can contribute to emission reduction by constraining supply, yet it may also result in cost inflation and reduced market efficiency. This highlights the significance of information asymmetry and strategic behavior between market-based tools and mandatory regulations [6]. Therefore, a careful balance between investment returns and renewable energy quotas is essential. To this end, evaluating carbon policies through life cycle analyses, particularly in rural hybrid energy systems, reveals the economic potential of negative carbon technologies [7]. Furthermore, when the impact of carbon taxation on hybrid system design is examined alongside reliability parameters, health and environmental co-benefits become more evident [8].

On the other hand, multi-objective optimization approaches are gaining increasing significance in energy system planning. Sharing strategies developed in decentralized distributed energy systems, for instance, have achieved a 14% reduction in both cost and carbon emissions [9]. In household-scale systems, life cycle-based multi-objective optimization has been emphasized as exposing the inadequacy of single-objective approaches [10]. Methods developed in literature have demonstrated improvements in technical performance and environmental sensitivity through the integration of optimal power flow and carbon pricing policies. One notable example is the hybrid particle swarm–grey wolf optimization (HPS-GWO) algorithm [11], which models the probabilistic distributions of solar and wind resources while incorporating the impact of carbon taxation, yielding cost and emission reductions over classical methods. However, the exclusion of hydroelectric resources and limited scenario diversity restrict the generalizability of these findings. Similarly, while the bird swarm algorithm (BSA) proposed in [12] considers renewable generation uncertainties, it has not been tested in large-scale applications [13]. In systems that ensure heat-electricity matching, multi-objective methodological frameworks improve energy efficiency and environmental impacts [14], whereas carbon tax incentive mechanisms in battery integration offer both economic and environmental gains [15]. Furthermore, Stackelberg game-based carbon-integrated pricing models have achieved up to 29% emission reductions [16]; nonetheless, the absence of realistic carbon market elements limits the model's validity. In hydrogen storage strategies, uncertainty management enables economic and environmental optimization, though extending the scope of realistic scenarios remains a key recommendation [17]. Overall, the optimization performance of metaheuristic algorithms, the positive role of carbon pricing in renewable energy integration, and the modeling of uncertainties stand out as critical factors. However, diversity in system types, large-scale scenario analyses, and technical detailing remain insufficient. Therefore, model generalizability, real data integration, and the development of comprehensive policy scenarios should be prioritized.

Apart from carbon tax, net metering is increasingly regarded as a critical incentive mechanism for the widespread adoption of distributed renewable energy systems. Numerous studies in this field have examined technical feasibility, economic payback period, and grid impacts of photovoltaic (PV) systems. However, many of these have insufficiently addressed contextual differences and the broader applicability of net metering schemes [18], [19]. For example, [18] investigates the performance of rooftop PV systems under different metering configurations in Lahore, Pakistan, highlighting the decisive role of net metering on the payback period. Nevertheless, the study has been criticized for methodological shortcomings, such as the omission of key economic indicators like net present value (NPV), which are crucial for investment decisions. Similarly, [19] reveals that the implementation of net metering in a PV + battery energy storage system (BESS) at an educational institution in India accelerates investment returns; however, regional regulations and grid capacity constraints limit the overall applicability of the system. A Ghana-based study [20], focusing on the challenges in the absence of metering infrastructure, introduces the concept of "integrated system efficiency" to reduce battery dependence and enhance direct energy use, proposing innovative metrics such as the "redundancy factor" instead of classical efficiency indicators. Nonetheless, the study's limitation to a single household reduces the generalizability of its findings. From an economic optimization perspective, [21] explores the contribution of net metering to system optimization in South Korea through machine learning-supported design, incorporating long-term meteorological and load forecasts. While this data-driven approach offers more accurate system sizing than conventional methods, its geographic scope remains limited, raising concerns about broader applicability. In scenario-based studies using software platforms such as hybrid optimization of multiple energy resources (HOMER Pro), net metering mechanisms have been shown to directly influence system design decisions. In off-grid regions of Pakistan, for instance, scenarios involving energy export to the grid can lead to negative net costs [22], while in Norwegian islands, the flexibility and cost-effectiveness

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of net metering are evaluated through scenario-based analyses [23]. These studies illustrate that investment returns are linked not only to technical adequacy but also to market accessibility and regulatory frameworks. However, how net metering practices are influenced by external factors such as social acceptance, infrastructure adequacy, and political stability remains insufficiently addressed [20], [22], [24]. Furthermore, issues introduced by digitalization, such as data security, real-time data transmission, and pricing algorithms, are particularly pronounced in prosumer-based systems [25]. This suggests that net metering should be examined not only in terms of economic feasibility but also as part of a broader socio-technical system. Ultimately, net metering has become one of the key policy instruments that enhance the economic viability of distributed generation technologies, especially PV systems. Nonetheless, empirical findings regarding how this mechanism functions across different geographic and socioeconomic contexts, what limitations it faces, and how it might be improved in the future remain diverse, and rarely converge into a comprehensive synthesis.

Another perspective has been proposed at the household level for PV systems. In this context, the effectiveness of net metering subsidies implemented in various regions of China was analyzed, revealing that uniform subsidy schemes, disregarding regional solar potential and variations in electricity demand, significantly limit economic efficiency [26]. The study recommends defining region-specific subsidy ranges and gradually adapting support mechanisms to market-based conditions in the long term. These findings reinforce the widely discussed theme of subsidy sustainability and emphasize the necessity for net metering policies to be sensitive to local contexts. Similarly, in [27], a PV–wind turbine (WT) hybrid system proposed for Northern Cyprus is expected to generate increased annual revenue through the implementation of net metering. However, the study lacks evaluation of battery capacity under alternative scenarios and offers limited stability analysis, highlighting the need for methodological improvement. This lack of technical depth is identified as a major barrier to the scalability and wider deployment of such systems. In the context of small and medium-sized enterprises, studies in northern regions of the United States indicate that off-grid systems integrating PV, battery storage, and diesel generators can be economically viable even without net metering support [28]. This suggests that net metering should not be viewed solely as an economic necessity, but rather as a policy tool that accelerates the energy transition. Nonetheless, the potential threat posed by these developments to electricity distribution companies calls for balanced approaches in energy policymaking. Regarding the long-term effectiveness of net metering and its relationship with grid reliability, several studies highlight those critical infrastructures, such as airports, can enhance their resilience to grid outages when supported by PV and battery systems within a microgrid framework [29]. However, the effects of net metering tariffs have yet to be fully integrated into detailed scenario analyses, once again underlining the need for incorporating policy parameters into system behavior models. In another residential area–based study, a grid-connected PV system implemented in the Uttarkhan region of Bangladesh led to a 53% reduction in energy costs and significant decreases in environmental impacts through the application of net metering [30]. While the use of lithium-ion batteries and real consumption data marks this study as innovative, it also points to the need for increased system flexibility through the proposed integration of biomass. At the macro level, the regulatory impacts of net metering were examined in the Brazilian context [31], where the mechanism was found to benefit distributed generation (DG) users; however, cost-shifting to non-DG users raised concerns over fairness. Issues such as energy justice, cost allocation for distribution infrastructure, and emerging tariff models are gaining importance not only technically but also politically. In the context of rural electrification, PV and biomass-based hybrid systems have been shown to be economically viable under net metering policies in India [32]. However, seasonal fluctuations in biomass availability and the long-term resilience of such systems remain key considerations for policymakers in evaluating sustainability and energy security dimensions.

The net metering system, which regulates the energy exchange between distributed energy producers and the electricity grid, plays a central role in the widespread adoption of renewable energy technologies. However, since its implementation methods and impacts vary across countries and regions, its technical and economic effectiveness must be evaluated from a multidimensional perspective. For instance, in the case of Poland, a comparison between net metering and feed-in-tariff (FiT) mechanisms revealed that the net metering regime provides a higher NPV at different system sizes (20 kWp and 40 kWp), making it more attractive to investors [33]. Similarly, in India, when comparing net metering with the zero-export regime, net metering was found to enable greater energy integration and economic return, whereas zero export significantly constrained efficiency. Studies on the technical configurations of net metering regimes particularly emphasize the critical role of metering methods. In this context, the Danish example examined the effects of different net metering approaches (phase-based, total energy flow-based, hourly or instantaneous measurement) on energy import, consumer behavior, and costs, revealing that minor technical differences can lead to substantial deviations in annual energy costs [34]. This finding indicates that regulatory authorities should carefully consider the strong correlation between technical choices and financial outcomes [35]. Tariffs implemented without advanced metering infrastructure (AMI) especially result in significant cross-subsidization, favoring low-production users and disadvantaging high-production users. Dynamic tariff structures such as time-of-use (ToU) and real-time pricing (RTP) have the potential to mitigate these imbalances [36]. A relevant study assessing this potential in Brazil noted that the proliferation of PV systems caused significant increases in conventional tariffs, which

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could adversely affect low-income groups. The sustainability of net metering regimes at the system level has also been examined from technical and economic perspectives [37]. In Egypt, a designed HRES was found effective in achieving net-zero energy and carbon goals, yet the lack of long-term field data posed limitations on its applicability. This underscores the importance of comprehensive scenario-based analyses considering local policy interactions. Moreover, the role of energy infrastructure and associated technologies on system efficiency is also highlighted. For example, optimizing the scheduling of solar-powered electric vehicle (EV) charging stations can reduce both energy costs and grid load by aligning PV production with charging demand [38]. However, these studies often overlook the influence of policymakers and diverse user profiles. Similarly, the technical and economic dimensions of hybrid PV-concentrated solar power (CSP)-electrolyzer systems have been analyzed, but the interactions between metering regimes or tariff structures and these systems have not been investigated in detail [39], [40].

Following net metering implementations, net billing mechanisms have emerged as models prioritizing self-consumption, whereby excess energy is sold back to the grid at a predetermined unit price. In recent years, net billing has been widely adopted in many countries and extensively studied regarding its impacts on renewable energy investments. This mechanism is predominantly observed in meter-based applications, and when examined within specific national contexts, developing a universal benefit-cost framework proves challenging. For instance, in the Caribbean, both net metering and net billing systems have been shown to increase PV installations and particularly align well with decentralized energy systems in small island states [41]. However, the combined consideration of these two models in the study limited the ability to isolate their individual effects. More detailed analyses conducted in Indonesia revealed that net metering provides higher user satisfaction and environmental benefits compared to net billing [42]. The financial impacts of transitioning to community-based structures were explored in Poland, where a shift to energy cooperatives under net billing resulted in cost reductions of up to 90% and shortened investment payback periods [43]. This suggests that while net billing offers limited investment incentives for individual users, it may operate more effectively in community-based models. Nevertheless, the integration of net billing with dynamic pricing systems and comparative evaluations of different metering mechanisms' economic impacts remain necessary. From the perspective of corporate profitability, net billing is considered advantageous; however, net metering is noted to be superior in consumer satisfaction and load reduction [44]. Investor-oriented support policies tend to be more prominent in this regard. Specifically, Poland's net billing scheme, under the new RES law, has reduced the attractiveness of PV investments, whereas net metering provides higher returns in hybrid systems involving heat pump integration [45]. In Saudi Arabia, net metering is regarded as the most feasible model for certain system sizes (10–20 kW), while net billing becomes preferable under specific conditions such as low module costs [46]. Investments in public buildings highlight the limitations imposed by net billing, where the evaluation of PV performance under atypical conditions and the extension of payback periods reduce its appeal and constrain economic returns [47]. Consequently, flexible models sensitive to consumption profiles are recommended over net billing for public investments. Declining PV installation costs, increased awareness of self-consumption, and sustainable energy targets contribute to the growing distinction of net billing from traditional net metering by compensating PV producers for excess energy fed into the grid at predefined rates [48], [49]. Spain's transition to net billing has yielded economic gains in residential PV installations, with systems sized 1.5–2 kWp identified as optimal in terms of investment payback and energy savings [48]. Moreover, net billing regulations facilitate positive internal rates of return across residential, commercial, and industrial sectors [49]. In this context, high retail electricity prices emerge as a key factor supporting profitability in the residential segment.

Net billing, which entails certain cost risks regarding system integration, can provide economic and environmental benefits through proper scaling and market regulations [49]. Comparative analyses conducted in Brazil indicate that net billing offers shorter payback periods and is more attractive for investment than net metering in four cities [50]. The proposed break-even price approach balances below the public tariff, making it investor-friendly without imposing additional burdens on system costs. It is emphasized that flexible and user-centric energy regulations are important policy tools to accelerate energy transition. Accordingly, Poland has transitioned to net billing; however, it is noted that net billing may have adverse short-term effects on low-power PV investments, and its economic viability improves when the self-consumption rate exceeds 50% or when supported by energy storage systems [51]. In Italy, optimization methods based on hourly consumption data are critical in net billing system design, yielding up to an 85% increase in NPV compared to traditional methods [52]. This highlights the need for more precise, data-driven approaches to capacity determination under net billing. In the long term, net billing systems encourage smarter and demand-responsive PV installations, with the transition contingent on appropriate market structures and regulatory support [53]. Particularly in developing countries, starting with simpler models such as net metering and gradually transitioning to net billing is seen as more efficient. Thus, despite encountering similar structural challenges across different regions, net billing's success appears feasible through holistic optimization.

Although previous studies have explored various configurations of hybrid renewable energy systems (HRES), there remains a lack of integrated assessments that simultaneously consider geographical diversity, consumer demand profiles, economic policy instruments, and energy billing mechanisms

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in a unified framework. Existing literature often focuses on isolated dimensions, such as technical feasibility, economic optimization, or environmental benefits, without sufficiently capturing the interplay between these factors in real-world policy settings. While some studies have discussed the role of carbon taxes or billing schemes individually, few have examined how these instruments interact across multiple regions and user types, especially under dynamic regulatory environments. Moreover, there is limited evidence regarding the application of such analyses in the Turkish context, where geographical diversity and policy design significantly affect system performance. This study addresses this gap by systematically synthesizing and extending previous research, while clearly identifying how the literature has treated each element, such as carbon pricing, metering strategies, and regional resource variability, and by introducing a comprehensive policy-aware optimization model that builds on these foundations.

Türkiye's energy transition process has become increasingly complex due to multidimensional pressures such as rising electricity demand, the need to reduce external dependency, and climate change targets. In this context, developing flexible and region-specific solutions that support the integration of renewable energy sources is of critical importance. The effects of measurement mechanisms such as net metering and net billing, as well as financial instruments like carbon taxation, on the performance of hybrid systems have not been sufficiently explored within the Turkish context. Existing regulations directly affect system design and feasibility by varying energy policies based on regional resource potential (e.g., Çanakkale's high wind capacity) and consumer profiles. This study aims to address current policy requirements at precisely this intersection. It offers a comprehensive analytical framework that considers regional differences, user types, and combined economic-policy scenarios for HRES applications in Türkiye. Recent volatility in energy prices, increasing global pressures on carbon emissions, and the reshaping of local support mechanisms for net metering underscore the timeliness of this issue. Moreover, advancements in energy storage technologies and enhanced simulation capabilities of decision-support tools like HOMER Pro enable more accurate multidimensional performance assessments of hybrid systems. Consequently, this study emerges from the need not only to optimize technical parameters but also to understand the interactions of policy and economic tools on the system. Within the dynamic environment shaping Türkiye's current energy policies, identifying the conditions under which HRES investments become more attractive provides strategic insights directly beneficial to policymakers, investors, and grid planners. In this respect, the research holds high relevance and originality in terms of both timing and application potential. This study provides significant insights to the HRES literature by addressing the often-overlooked intersections of regulatory policies and geographic diversity through a comprehensive multi-scenario analysis centered on Türkiye. Specifically, it offers the following key contributions:

- Develops an innovative multi-scenario evaluation framework that explicitly captures Türkiye's climatic diversity and sector-specific demand patterns by simulating hybrid renewable energy systems across four climatically distinct cities and three consumer categories (residential, commercial, industrial). This approach fills a critical gap in context-sensitive HRES planning, going beyond the predominantly single-region or mono-sector focus in existing research.
- Presents one of the first comprehensive, policy-aware quantitative comparisons of NM and NB under real-world tariff structures and carbon pricing. The analysis reveals nuanced trade-offs: NM significantly reduces costs and maximizes renewable penetration in wind-rich commercial sectors, while NB encourages battery integration and economic discipline under higher carbon tax scenarios. These insights directly support improved tariff design and regulatory frameworks for emerging energy markets.
- Integrates dynamic carbon taxation scenarios into techno-economic optimization models, providing strong evidence of their crucial role in accelerating renewable energy adoption, reducing levelized costs, and reshaping investment priorities within distributed hybrid systems, a dimension often neglected in previous studies.
- Extends evaluation metrics beyond traditional financial indicators by including advanced operational performance measures such as self-supply rate, self-consumption rate, and energy exchange rate. This provides a more comprehensive understanding of system efficiency and flexibility.
- Provides actionable, location-specific investment and policy recommendations aligned with Türkiye's national energy transition goals, emphasizing equitable access, affordability, and regional resource optimization. This policy-focused framework serves as a replicable model for similar emerging economies striving to balance sustainability, economic viability, and energy security.

This paper is structured as follows: Section I introduces the research context, objectives, and provides a literature review. Section II details the materials and methods used, including system modeling, case areas, scenario definitions, and the objective and decision criteria. Section III presents and analyzes the optimization results. Section **??** investigates the sensitivity of hybrid energy systems to various tariff structures and carbon tax levels. Section V compares different policy mechanisms and evaluates their effectiveness. Section VI provides an in-depth discussion of the findings. Finally, Section VII concludes the study and suggests directions for future research in hybrid energy systems and energy policy development.

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II. MATERIAL AND METHODOLOGY

In this study, the optimization process was conducted using the default configuration of HOMER Pro, which operates based on its internal search space and optimization algorithm module. HOMER Pro primarily employs a grid-search-like enumerative approach, systematically evaluating all feasible combinations of system components (e.g., PV, wind turbine, battery, converter, grid connection) and dispatch strategies across the defined techno-economic search space. This process is commonly referred to as exhaustive search or brute-force optimization, where the software attempts to find the globally optimal configuration by simulating and ranking a large set of possible system designs. Unlike traditional metaheuristic algorithms (e.g., genetic algorithms, particle swarm optimization), which rely on iterative convergence and stochastic sampling, HOMER's optimization strategy does not depend on convergence criteria or involve risks of local minima entrapment. Instead, by evaluating discrete combinations exhaustively, it inherently avoids premature convergence and trapping in suboptimal regions, making the optimization deterministic and reproducible. Furthermore, since HOMER Pro's optimization routine is not user-programmable at the algorithmic level, this study relied on the software's default search resolution and accuracy settings as provided upon installation. These defaults include pre-set discretization levels for each decision variable and system component size, ensuring consistency and standardization across all scenario analyses. Although this brute-force method increases computational intensity, it enhances robustness by thoroughly covering the solution landscape, particularly useful for HRES studies with multiple interacting technologies and constraints. This optimization setup allowed the study to evaluate the techno-economic and environmental feasibility of hybrid systems across varying policy and regional scenarios without bias from algorithmic randomness or user-defined convergence behavior.

A. SYSTEM MODELING

The developed hybrid power system (HPS) integrates RES (PV and WT) with battery storage technology to provide efficient and sustainable energy management (see Fig. 1). This system optimizes the balance between energy production and storage, stabilizing the variability of renewable resources and ensuring continuous energy supply. The AC load, capable of exchanging energy with the grid, enhances energy efficiency and reduces carbon emissions, providing economic benefits.

The PV module serves as a fundamental component in a HPS. The performance of the PV array is influenced by several factors, including incident solar radiation, panel temperature, the efficiency of the PV panels, and the derating factor (DF). The power output of the PV array at any given time t is represented by Equation (1) [54], while the maximum efficiency under standard test conditions (STC) is described by Equation (2) [55]. Additionally, the formula for determining the cell temperature of the PV array under operating conditions is specified in Equation (3) [56].

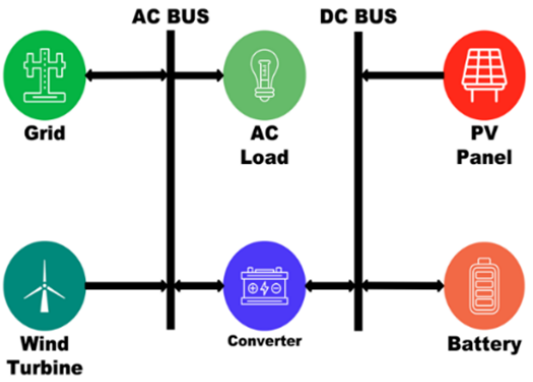


FIGURE 1. Modeling of proposed architecture

$$P_{\mathrm{PV}}^{t} = P_{\mathrm{PV}}^{stc} \cdot f_{\mathrm{PV}} \cdot \frac{IR_T^t}{IR_T^{\mathrm{stc}}} \left[1 + \alpha_P (T_C^t - T_C^{\mathrm{stc}})\right], \quad \forall t \tag{1}$$

$$\eta_{\mathrm{mp}}^{\mathrm{stc}} = \frac{P_{\mathrm{PV}}^{stc}}{A_{\mathrm{PV}} \cdot IR_T^{\mathrm{stc}}}, \quad \forall t \tag{2}$$

$$T_C^t = \frac{T_a^t + (T_c^{\mathrm{NOCT}} - T_a^{\mathrm{NOCT}}) \frac{G_T^t}{G_T^{\mathrm{NOCT}}} \left[1 - \frac{\eta_{\mathrm{mp}}^{\mathrm{stc}}(1 - \alpha_P T_C^{\mathrm{stc}})}{\tau\alpha}\right]}{1 + (T_c^{\mathrm{NOCT}} - T_a^{\mathrm{NOCT}}) \frac{G_T^t}{G_T^{\mathrm{NOCT}}} \frac{\alpha_P \eta_{\mathrm{mp}}^{\mathrm{stc}}}{\tau\alpha}} \tag{3}$$

The actual output power of the PV system (P_{PV}^t) is influenced by several factors, including the nominal capacity of the PV panel under STC (P_{PV}^{stc}), the derating factor of the PV panel (f_{PV}), incident solar radiation, and the temperature of the PV cells under both standard and operational conditions (IR_T^t, IR_T^{stc}, T_C^t, and T_C^{stc}), as well as the temperature coefficient of the power (α_P). The maximum efficiency of the PV panel under STC ($\eta_{\mathrm{mp}}^{\mathrm{stc}}$) is determined by the nominal capacity of the PV panel under standard conditions, the panel area (A_{PV}), and the incident radiation at standard conditions.

The temperature of the PV cells is influenced by various factors, including the solar radiation incident on the PV array (G_T^t), the solar transmittance of any covering over the PV array (τ), the solar absorptance of the PV array (α), the nominal operating cell temperature (NOCT) (T_c^{NOCT}), the ambient temperature at which NOCT is defined (20°C, T_a^{NOCT}), and the level of solar radiation at which NOCT is measured (0.8 kW/m^2, G_T^{NOCT}).

The PV system is characterized by a capital cost of 1000 \$/kW and a replacement cost of 800 \$/kW. The annual operation and maintenance (O&M) cost is estimated at 10 \$/kW/yr [57]. The system operates with a degradation factor of 80%, and the ground reflectance is considered to be 8% [58].

For efficient WT operation, it is essential to consider factors such as wind speed, turbine performance characteristics, and environmental conditions. The power output of a WT is primarily influenced by wind speed at a specific elevation, along with atmospheric parameters. The mathematical models used to estimate power output incorporate various factors that impact the turbine's energy generation potential. One

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key equation describes the relationship between the turbine's hub height and the anemometer height, while another relates the turbine's power output to air density under standard atmospheric conditions. These parameters, along with associated energy losses, significantly influence turbine efficiency. By quantifying their impact on energy production, system performance can be optimized. Specifically, to determine the WT's power output, it is first necessary to calculate the wind speed at the hub height, as shown in Equation (4) [59].

$$\frac{U_{\text{hub}}}{U_{\text{anem}}} = \frac{\ln\left(\frac{H_{\text{hub}}}{H_0}\right)}{\ln\left(\frac{H_{\text{anem}}}{H_0}\right)} \tag{4}$$

In this context, U_{hub} represents the wind speed at the hub height, U_{anem} is the wind speed measured at the anemometer height, H_{hub} denotes the hub height of WT, H_{anem} is the height of the anemometer, and H_0 refers to the surface roughness length. The power output of the WT is subsequently calculated based on the air density and the reference power output under standard conditions (see Equation (5)) [59], [60].

$$\frac{P^{\text{WT}}}{P^{\text{WT}}_{\text{STP}}} = \frac{\rho}{\rho^0} \tag{5}$$

In this equation, P^{WT} denotes the power output of the WT, ρ represents the actual air density, ρ^0 is the air density under standard temperature and pressure conditions, and $P^{\text{WT}}_{\text{STP}}$ refers to the turbine's power output under standard conditions. WTs are subject to various types of losses, which have a direct impact on their overall energy production performance. Table 1 presents the percentage distribution of these losses [61]. These loss parameters are essential for accurately estimating the actual energy yield from WTs, as they account for real-world deviations from ideal operating conditions. Each type of loss represents a distinct factor that negatively influences turbine output. For instance, availability losses (6.0%) stem from scheduled and unscheduled maintenance activities, while performance losses (2.5%) reflect sub-optimal control strategies, mechanical aging, or equipment wear. Environmental losses (2.6%) capture the effects of adverse conditions such as icing, soiling, and turbulence. Shadowing losses (6.7%) occur due to wake effects in wind farms, where upstream turbines obstruct airflow to downstream units. Electrical losses (2.1%) arise from transmission and conversion inefficiencies within the system. Constraint losses, although relevant in certain regulatory or grid-constrained contexts, are excluded from this study due to their high site-specific variability. Collectively, these losses contribute to an approximate 20% reduction in gross wind power output, which significantly impacts the economic viability and operational performance of the hybrid system. Therefore, incorporating these loss factors into the modeling and optimization framework is essential for ensuring realistic, reliable, and bankable energy yield projections. Furthermore, the capital cost, replacement cost, and operation and maintenance (O&M) cost are assumed to be 2000 $/kW, 1800 $/kW, and 30 $/kW/yr, respectively, with a hub height of 27.5 meters [62], [63].

TABLE 1. Wind turbine loss parameters

Parameter Names	Value	Units
Availability losses	6.0	%
Performance losses	2.5	%
Environmental losses	2.6	%
Shadowing losses	6.7	%
Electrical losses	2.1	%
Constraint losses	-	%

The proper allocation of the ESS is essential for the efficient functioning of the HPS and for the storage of CE. The energy output of the ESS is governed by its charging and discharging states, which are represented by the state of energy (SoE_t^{ESS}). The energy state of the ESS is determined using Equation (6), which takes into account the charging and discharging efficiencies (η_{chr} and η_{disch}), along with the corresponding power inputs ($P_t^{ESS_{chr}}$ and $P_t^{ESS_{disch}}$), while also considering its energy state at the previous time step (SoE_{t-1}^{ESS}) [64]. Furthermore, Equation (7) demonstrates that the aging process of the ESS confines its energy state to a range between 20% and 90%.

$$SoE_t^{ESS} = SoE_{t-1}^{ESS} + P_t^{ESS_{chr}} \cdot \eta_{chr} - \frac{P_t^{ESS_{disch}}}{\eta_{disch}}, \quad \forall t \tag{6}$$

$$SoE^{ESS}_{\max} \geq SoE_t^{ESS} \geq SoE^{ESS}_{\min}, \quad \forall t \tag{7}$$

A fresh ESS is modeled using a modified advanced storage (ASM) approach, incorporating four distinct Arrhenius-based sub-models: the functional model, the temperature and relative capacity model, the depth of discharge (DoD)-dependent cycle life model, and the temperature-dependent shelf life model. Power loss and theoretical capacity are calculated using Equations (8) and (9) [65].

$$P^{ESS}_{\text{out}} = V_0 I - R_0 I^2 \tag{8}$$

$$I^{\max}_{P_{\text{out}}} = \frac{V_0}{2R_0} \tag{9}$$

In this context, P^{ESS}_{out} denotes the output power of the ESS, while V_0, R_0 and I represent the nominal voltage, series resistance, and current of the ESS, respectively. The current corresponding to the maximum output power of the ESS is referred to as $I^{\max}_{P_{\text{out}}}$.

The temperature-dependent capacity is determined by considering both the temperature and the specific characteristics of the battery, which are described by the constants d_0, d_1, d_2, as outlined in Equation (10) [66]. The cycle degradation curves for each DoD can be obtained either from the battery manufacturer or calculated through Equations (11) and (12) [67]. Even in the absence of active use, the ESS may experience capacity degradation due to temperature-induced calendar aging. The aging effect, modeled using the Arrhenius equation, is represented in Equation (13) [55].

$$C^{\text{ESS}}_{T_{\text{avail}}} = C^{\text{ESS}}_{T_{\text{nom}}} \cdot (d_0 + d_1 T + d_2 T^2) \tag{10}$$

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$$\frac{1}{N} = A \cdot \mathrm{DoD}^{\beta} \tag{11}$$

$$D = \sum_{i=0}^{N} (A \cdot D_i^{\beta}) \tag{12}$$

$$k_t = B \cdot e^{-\frac{d}{T}} \tag{13}$$

In this context, the ESS capacity, based on the available temperature, is represented as $C^{\mathrm{ESS}}_{T_{\mathrm{avail}}}$, while the ESS capacity corresponding to nominal temperature conditions is denoted by $C^{\mathrm{ESS}}_{T_{\mathrm{nom}}}$. The curve parameters are denoted by d_0, d_1 and d_2, with T representing the available temperature of the ESS. The coefficient A signifies the DoD factor, while DoD^{β} refers to the DoD exponent fit, and N represents the project year. Additionally, D is the exponential degradation coefficient, which incorporates both time- and temperature-dependent degradation, and k refers to the storage rate constant (h^{-1}).

The maximum charging and discharging power of the ESS are calculated at each time step. The charging power dictates how much excess renewable energy can be absorbed by the system. These maximum power values fluctuate with each time step based on the state of charge (SoC). Three primary constraints are applied to the maximum charging power of the ESS. The first constraint is derived from the kinetic battery model, which determines the maximum discharge power, as specified in Equation (14). The second constraint, the maximum charge C-rate, is calculated as described in Equation (15). The third limitation involves the maximum charging current of the ESS, which is determined according to Equation (16). Ultimately, the maximum charging power is obtained by minimizing these three constraints, as shown in Equation (17). The maximum discharge power during any given operational period is determined by Equation (18), while the maximum usable discharge power is defined by Equation (19) [68].

$$P^{\mathrm{ESS}}_{c_{\mathrm{max,\,kbm}}} = \frac{kQ^{\mathrm{ESS}}_{\mathrm{avail}} e^{-k\Delta t} + Q^{\mathrm{ESS}}_{\mathrm{init}} kc(1-e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{14}$$

$$P^{\mathrm{ESS}}_{c_{\mathrm{max,\,mcr}}} = \frac{(1-e^{-\alpha_c \Delta t})(Q^{\mathrm{ESS}}_{\mathrm{max}} - Q^{\mathrm{ESS}}_{\mathrm{init}})}{\Delta t} \tag{15}$$

$$P^{\mathrm{ESS}}_{c_{\mathrm{max,\,mcc}}} = \frac{N_{\mathrm{bat}} \cdot I_{\mathrm{max}} \cdot V_0}{1000} \tag{16}$$

$$P^{\mathrm{ESS}}_{c_{\mathrm{max}}} = \frac{\min\left(P^{\mathrm{ESS}}_{c_{\mathrm{max,\,kbm}}}, P^{\mathrm{ESS}}_{c_{\mathrm{max,\,mcr}}}, P^{\mathrm{ESS}}_{c_{\mathrm{max,\,mcc}}}\right)}{\sqrt{\eta^{\mathrm{ESS}}_{\mathrm{rt}}}} \tag{17}$$

$$P^{\mathrm{ESS}}_{d_{\mathrm{max,\,kbm}}} = \frac{-kcQ^{\mathrm{ESS}}_{\mathrm{max}} + kQ^{\mathrm{ESS}}_{\mathrm{avail}} e^{-k\Delta t} + Q^{\mathrm{ESS}}_{\mathrm{init}} kc(1-e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{18}$$

$$P^{ESS}_{d_{\mathrm{max}}} = \sqrt{\eta^{ESS}_{rt}} \cdot P^{ESS}_{d_{max,kbm}} \tag{19}$$

In this context, c denotes the ratio of storage capacity, Δt represents the duration of each time step (measured in hours), and Q_{max} refers to the total energy capacity of the storage system (in kWh). The symbol α_c indicates the maximum charge rate of the storage (in A/Ah), while N_{bat} represents the total number of batteries in the storage system. Additionally, I_{max} signifies the peak charging current (in A), V_0 is the nominal voltage of the storage system, and η^{ESS}_{rt} stands for the round-trip efficiency of the battery storage system (in %).

Table 2 provides a detailed summary of the key technical parameters and aging curve coefficients used to model the performance and degradation behavior of a fresh lithium-ion battery pack integrated into the ESS. These parameters are directly incorporated into the mathematical equations of the ESS model to simulate dynamic behavior, efficiency losses, and lifetime degradation under various operational scenarios [93]. These values are based on the Generic 1kWh Li-Ion advanced storage model provided in the HOMER Pro simulation platform. The selected configuration represents a 1.02 kWh generic battery unit, reflecting average characteristics of commercially available lithium-ion batteries. HOMER's default model incorporates industry-informed values that are generally aligned with specifications from leading battery manufacturers such as Tesla (Powerwall), LG Chem (RESU series), and Panasonic (NCR series). However, these values do not directly correspond to a specific commercial product but rather represent a standardized, vendor-neutral profile suitable for techno-economic simulations. Here, the useful capacity (1.02 kWh) and nominal voltage (3.7 V) define the initial energy storage capability and operating conditions of a single battery module. Maximum charge/discharge currents and capacity (Ah) specify the upper operational limits, which are critical for system sizing and power management, particularly during peak load or rapid charging/discharging events. The rate constant (79.288 1/hr) and effective series resistance (0.36049 mΩ) directly influence the dynamic behavior of the battery in transient simulations and efficiency calculations. These parameters are used in the equivalent circuit model to predict internal losses and voltage response under varying loads. Temperature-related limits (0–50°C) reflect the safe operating range of the battery chemistry. Exceeding these bounds may accelerate degradation or lead to thermal runaway. Therefore, thermal management strategies are considered in system operation logic. The round-trip energy loss of 8% accounts for internal losses and conversion inefficiencies during charge/discharge cycles. This parameter affects both economic performance and energy balance in HOMER Grid or equivalent simulation platforms. Initial and minimum SoC thresholds (100% and 20%, respectively) are defined to avoid deep discharging, which is known to significantly reduce battery life. The degradation limit of 50% state of health (SOH) marks the end-of-life (EoL) threshold, beyond which the battery is considered no longer viable for grid-interactive applications. EoL is determined by comparing calendar aging and cycling degradation, with the more dominant mechanism defining the operational lifetime. The cycling degradation model employs DoD curves, using parameters A and β, to estimate cycle life based on usage intensity. Similarly, calendar degradation is modeled using temperature-dependent shelf-life equations with parameters B and d. Finally, the curve-fitting parameters (d_0, d_1, d_2) for relative capacity vs. temperature enable the model to dynamically adjust per-

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formance metrics under varying climatic conditions, which is particularly relevant for simulations across multiple geographical regions. By incorporating these comprehensive and empirically grounded parameters, the model can simulate realistic degradation trajectories, operational constraints, and performance metrics for the ESS under various usage scenarios. The capital cost is assumed to be 350 $/kWh, while the replacement cost is set at 300 $/kWh. Additionally, the annual operation and maintenance (O&M) cost is estimated at 5 $/kWh.yr.

Converters play an essential role in enabling the transfer of energy between DC and AC systems within a HPS. Typically, these devices consist of both a rectifier and an inverter. Accurate sizing of the converter is crucial for maintaining the precision of the HPS model. An undersized converter can lead to significant energy losses and inefficiencies. The power output equation for the inverter is presented in Equation (20), whereas the rectifier's power output is described in Equation (21).

$$P_{\text{inv}}^{t} = \eta_{\text{inv}} \cdot P_{\text{DC}}^{t}, \quad \forall t \tag{20}$$

$$P_{\text{rec}}^{t} = \eta_{\text{rec}} \cdot P_{\text{AC}}^{t}, \quad \forall t \tag{21}$$

In this context, the power outputs of the converter (or power conversion system (PCS)) in inverter mode (P_{inv}^{t}) and rectifier mode (P_{rec}^{t}) are evaluated. The efficiencies (η_{inv} and η_{rec}) as well as the AC and DC output powers (P_{AC}^{t} and P_{DC}^{t}) are considered for both inverter and rectifier operations. The capital and replacement cost of the converter has been set at 300 $/kW [69]. Here, the converter, functioning as both an inverter and a rectifier, has an inverter and rectifier efficiency of 95%, with relative efficiency considered to be 100%.

To account for variations in electricity consumption patterns and cost structures among different consumer types, the study considers three primary consumer categories: residential, commercial, and industrial. This classification enables a more comprehensive analysis of diverse consumption behaviors and their associated economic implications. The annual energy consumption values for each group are as follows: residential consumers use 4,105 kWh, commercial consumers use 884,050 kWh, and industrial consumers consume 8,751,839 kWh.

Another component relevant to the system architecture is the electrical grid. In this context, the electricity tariffs associated with the grid and the applicable carbon tax rates are of particular importance. Tariffs established by regulatory bodies such as Türkiye's Energy Market Regulatory Authority (EPDK) play a critical role in determining the feasibility of renewable energy projects. The environmental and economic performance of these projects is also influenced by the CO_2 emission factor of 426.10 g/kWh and the electricity price of 0.017 $/kWh under the single-rate grid tariff structure [70]. Time-of-use (ToU) tariff structures vary across different sectors, further affecting system economics. Electricity tariffs vary by load type and time period, with residential rates at 0.0493, 0.0935, and 0.0140 $/kWh for flat, peak, and valley periods respectively; commercial rates at 0.1073, 0.1791, and 0.0502 $/kWh; and industrial rates remaining relatively stable at 0.0493, 0.0502, and 0.0465 $/kWh for the same periods. The ToU pricing model, which divides the day into peak, flat, and valley periods with different electricity rates, reflects the temporal variability of electricity demand and supply. Incorporating the ToU structure into the energy system model allows for dynamic operational strategies, such as charging the ESS during valley periods with lower prices and discharging during peak periods to avoid higher grid costs. This approach enhances the system's economic performance by maximizing arbitrage opportunities and improves grid support through load leveling. Moreover, the tariff classification by consumer category (residential, commercial, industrial) enables tailored economic analysis according to differing load profiles, consumption behaviors, and sector-specific incentives. This inclusion ensures that the techno-economic simulation accounts for both temporal and sectoral electricity cost variability, thereby enhancing the realism and decision-making relevance of the study.

Grid interaction plays a key role in integrating renewable energy systems, particularly in the context of variable solar generation. As solar availability fluctuates geographically and temporally, various countries have adopted different billing mechanisms to enhance grid flexibility and promote renewable energy utilization. Among these, Net Metering allows consumers to export surplus electricity to the grid and receive credits, which can later offset their consumption. These credits may be carried forward monthly or settled based on demand. While net metering offers significant operational flexibility, its application is limited by available grid capacity. In contrast, Net Billing compensates users for CE exported to the grid at a fixed, typically wholesale, rate. Energy imported from the grid is billed at the standard retail rate. This price disparity can incentivize users to integrate ESS for maximizing self-consumption. Although net billing may reduce the financial return compared to net metering, it encourages greater energy independence and grid stability. Both mechanisms offer distinct advantages for prosumers and regulatory bodies and were assessed under varying regional, consumption, and policy scenarios.

Türkiye's renewable energy policy framework began with the enactment of the Renewable Energy Law in 2005, introducing the Renewable Energy Resources Support Mechanism (YEKDEM) to stimulate investment in green energy. This framework included benefits such as exemptions from customs duties and value added tax (VAT), reduced transmission fees, and a guaranteed FiT of 0.133 $/kWh for ten years. These incentives contributed significantly to the expansion of the country's renewable energy capacity.

Subsequent regulatory developments, such as the 2019 amendment to the unlicensed electricity production regulation, enabled consumers to install on-site renewable generation systems without the need for distribution infrastructure, provided that production and consumption occur at the same metering point. Public institutions were later allowed to

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TABLE 2. Technical parameters for fresh battery pack

Parameters	**Fresh Battery (FB)**
Useful Capacity [kWh]	1.02
SOH [%]	100
Nominal Voltage [V]	3.7
Max. Charge Current [A]	270
Max. Discharge Current [A]	810
Max. Capacity [Ah]	270.27
Rate Constant [1/hr]	79.288
Capacity Ratio	1
Effective Series Resistance [mΩ]	0.36049
Max. Operating Temperature [°C]	50
Min. Operating Temperature [°C]	0
Other Round-trip Losses [%]	8
Initial SoC [%]	100
Min. SoC [%]	20
Degradation Limit [%]	50
End of Life (EoL)	
Calculate EoL by	Calendar or cycling degradation, whichever is greater
Cycling degradation uses DoD based on	Degraded battery capacity
Curve Parameters	
Relative Capacity vs. Temperature	d_0: 0.923
	d_1: 0.00345
	d_2: -0.0000375
DoD vs. Cycles to Failure	A: 0.00014423
	β: 1.7945
Shelf-Life vs. Temperature	B: 1.267
	d: 3826.70644

install such systems on rooftops, facades, or land, even when production and consumption sites differ, provided contractual limits are not exceeded.

For small-scale systems, up to 10 kW for residential systems and 5 MW for other sectors, excess electricity can now be sold back to the grid. Monthly netting has also been introduced, and suppliers are required to purchase surplus electricity at rates regulated by EPDK for a ten-year period.

Despite these advancements, several challenges continue to impede rapid deployment. These include frequent policy changes, legal ambiguities, financing difficulties, bureaucratic hurdles, and limited infrastructure and technical capacity. High interest rates remain a major financial barrier, and current incentive schemes largely focus on fixed supports for self-consumption models, particularly for rooftop PV systems under 10 kW. Unlike many developed nations, Türkiye has not yet adopted tiered or hybrid incentive models.

To overcome these challenges, it is essential to expand the scope of financial incentives, such as offering region-specific FiTs, supporting battery storage technologies, and shortening investment payback periods through foreign financing. The introduction of hybrid policy mechanisms tailored to self-consumption and installed capacity could significantly accelerate the country's transition toward sustainable energy and environmental goals.

On the other hand, in project optimization, several key parameters significantly influence economic performance, and these parameters are often shaped by a country's specific economic, environmental, and regulatory landscape. Critical factors include the project lifetime, inflation rate, interest rate, discount rate, electricity tariffs determined by regulatory authorities, and the CO_2 emission factor associated with grid electricity consumption. For this study, the project lifetime is assumed to be 25 years, which is essential for determining the payback period and assessing long-term viability. An inflation rate of 50% has been considered, affecting operational, energy, and capital expenditures, and consequently influencing financial indicators such as the internal rate of return (IRR) and NPC. A discount rate of 43.25% is applied to evaluate future cash flows, reflecting the high cost of capital and financial risk in the given context [71].

B. CASE AREAS

Cities from different geographical and climatic regions of Türkiye were selected for a comparative assessment of their suitability for photovoltaic (PV) and wind turbine (WT) applications. The selection was based on two primary criteria: high Global Horizontal Irradiance (GHI) for evaluating PV potential, and elevated average wind speeds at 100 m anemometer height for assessing WT feasibility. This strategic selection approach highlights the regional disparities in renewable energy potential and provides a foundation for hybrid system optimization under diverse meteorological conditions.

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The selected case areas and their corresponding renewable energy characteristics are summarized in Table 3 [72], [73]. Antalya, located on the Mediterranean coast, demonstrates high PV potential due to strong GHI values and extended sunshine duration; however, it possesses relatively limited wind resources. Çanakkale, situated in the northwestern part of the country near the Aegean Sea, exhibits strong wind energy potential supported by high average wind speeds and WT-specific power, while its solar potential remains moderate. Isparta, located inland in southwestern Türkiye, presents a well-balanced renewable energy profile with favorable metrics for both PV and WT systems. In contrast, Düzce, positioned along the Black Sea coast, displays limited renewable potential for both technologies, primarily due to lower solar irradiation and moderate wind speeds influenced by the region's humid and cloudy marine climate. Table 3 summarizes key site-specific parameters such as solar irradiance components (DNI, DHI, GTI), optimum PV tilt angles, air temperature, wind speed, specific energy outputs for PV and WT, and average sunny and rainy days [74], [75]. These data form the basis for assessing the technical and environmental feasibility of hybrid renewable energy systems at each location.

C. OVERVIEW OF ANALYZED SCENARIOS

This study examines 48 distinct scenarios by integrating four climatically diverse cities, three load profiles (residential, commercial, industrial), two carbon tax levels, and two metering methods (net metering and net billing). The analysis evaluates how combinations of geographical characteristics, sector-specific demand patterns, carbon taxation, and tariff structures influence energy costs, renewable penetration, and system performance. Additionally, a sensitivity analysis was conducted by varying carbon tax rates from 0 to 100 \$/tCO_2 and applying grid electricity price multipliers between 1.0 and 2.0 to assess system behavior under evolving policy and market conditions. These comprehensive scenario assessments provide a robust, policy-relevant framework to guide hybrid renewable energy system design and deployment in Türkiye and comparable emerging economies. A summary of the analyzed scenarios is presented in Table 4.

D. OBJECTIVE AND DECISION CRITERIA

To determine the net present cost (NPC), it is crucial to analyze the various cost components associated with the HPS. The discount rate (DR) and the capital recovery factor (CRF), which are essential for the calculations, are computed using Equations (22) and (23) [76]. Based on these values, the initial investment is determined through Equation (24), while the maintenance cost is derived from Equation (25). The replacement cost is calculated following the procedures outlined in Equations (26), (27), and (28). Additionally, the sinking fund factor (SSF) is utilized to scale the future value of a series of equal annual cash flows, as detailed in Equation (26). The scale factor and the remaining service life required for the economic evaluation are determined using Equations (27) and (28). With these calculations, the replacement cost is subsequently determined through Equation (29), while the penalty from the carbon tax is calculated using Equation (30). The electricity purchase cost is obtained via Equation (31), and the revenue from sales is derived from Equation (32) [55]. Finally, the cumulative financial sum of the system at the end of the year is expressed by Equation (33) [77]. In this equation, costs are combined through a linear sum to represent the system's total annual financial impact. Each cost component is calculated based on actual monetary values and parameters such as tax rates and replacement intervals. Although this approach does not explicitly apply different weights to cost components, their relative importance is inherently reflected through their respective magnitudes. Future studies may consider multi-objective optimization frameworks that assign explicit weights or priorities to different cost factors to address decision-maker preferences more comprehensively.

$$i = \frac{i' - f}{1+f} \tag{22}$$

$$CRF\,(i,N) = \frac{i.(1+i)^n}{i.(1+i)-1} \tag{23}$$

$$C_{\text{inv}} = \text{CRF}(i,N) \cdot \sum_l \left(IC^l \cdot C^l_{\text{cap}} \right) = \text{CRF}(i,N) \cdot C^{\text{tot}}_{\text{cap}} \tag{24}$$

$$C_{\text{main}} = \varepsilon \cdot \sum_l \left(IC^l \cdot C^l_{\text{cap}} \right) = C^{\text{tot}}_{\text{cap}} \cdot (1+i)^N \tag{25}$$

$$\text{SSF}(i,N) = \frac{i}{(1+i)^N - 1}\,;\, \text{SSF}(i,N_{\text{comp}}) = \frac{i}{(1+i)^{N_{\text{comp}}} - 1} \tag{26}$$

$$f_{\text{RC}} = \begin{cases} 0 & \text{if } N_{\text{RC}} = 0 \\ \frac{\text{CRF}(i,N)}{\text{CRF}(i,N_{\text{RC}})} & \text{if } N_{\text{RC}} > 0 \end{cases} \tag{27}$$

$$\begin{aligned} N_{\text{rem}} &= N_{\text{comp}} + N_{\text{rep}} - N \\ &= N_{\text{comp}} + \left(N_{\text{comp}} \cdot \text{INT}\left(\frac{N}{N_{\text{comp}}} \right) \right) - N \end{aligned} \tag{28}$$

$$C_{\text{rep}} = C_{\text{RC}} \cdot f_{\text{RC}} \cdot \text{SSF}(i,N_{\text{comp}}) - C_{\text{RC}} \cdot \frac{N}{N_{\text{comp}}} \cdot \text{SSF}(i,N) \tag{29}$$

$$C_{\text{tax}} = CO^{\text{tax}}_2 \cdot \lambda \cdot \sum_t E^t_{\text{GP}} = CO^{\text{tax}}_2 \cdot TCO_2 \tag{30}$$

$$C_{\text{GP}} = \sum_t E^t_{\text{GP}} \cdot C^t_{\text{purch}} \tag{31}$$

$$C_{\text{GS}} = \sum_t E^t_{\text{GS}} \cdot C^t_{\text{sell}} \tag{32}$$

$$C^{tot}_{\text{ann}} = C_{\text{inv}} + C_{\text{main}} + C_{\text{rep}} + C_{\text{tax}} + C_{\text{GP}} - C_{\text{GS}} \tag{33}$$

In this context, C_{inv} represents the initial investment cost (\$/yr), while C_{main} denotes the total maintenance cost (\$/yr). C_{rep} corresponds to the average annual replacement cost (\$/yr), and C_{tax} refers to the total carbon tax (\$/yr). C_{GP} is the total cost associated with purchasing electricity (\$/yr), whereas C_{GS} represents the revenue generated from selling electricity (\$/yr). The capacity of the HPS components is denoted by IC^l (kWh), and C^l_{cap} indicates the capital cost of the HPS components (\$). $C^{\text{tot}}_{\text{cap}}$ represents the total capital cost of the current system (\$). The maintenance factor for

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TABLE 3. Geographical data for the case areas (at 100 m anemometer height)

Parameters	Antalya	Düzce	Canakkale	Isparta	Units
Specific PV power	3.86–4.96	3.18–3.72	3.69–4.47	3.92–4.74	kWh/kWp
DNI	4.07–6.01	2.93–3.82	3.74–5.04	4.18–5.65	kWh/m^2
GHI	4.34–5.22	3.55–3.97	4.08–4.76	4.34–5.01	kWh/m^2
DHI	1.46–1.80	1.56–1.75	1.63–1.79	1.53–1.73	kWh/m^2
GTI	4.79–6.01	3.89–4.49	4.52–5.44	4.83–5.75	kWh/m^2
Optimum tilt	29–34	30–32	29–32	30–34	°
Air temperature	3.1–21.3	7.4–14.9	11–17	4.6–17.4	°C
Average wind speed	7.14	5.07	8.63	7.55	m/s
Specific WT power	642	268	730	662	W/m^2
Average sunny days	318	277	313	268	days
Average solar irradiation	8.1	5.1	7.2	7.1	hrs
Annual rainy days	73.2	133.6	83.9	98.8	days

TABLE 4. Scenarios

Case Areas	Scenarios	Load Profile	Tariff Scheme	Carbon Tax
Antalya Çanakkale Isparta Düzce	1–48	Residential, Commercial, Industrial	Net Metering, Net Billing	0 and 40 \$/tCO$_2$

Note: A sensitivity analysis was conducted by varying the carbon tax (0–100 \$/tCO$_2$) and applying grid electricity price multipliers (1.0–2.0) to evaluate system performance under evolving policy and market conditions.

the HPS is denoted by ε refers to the replacement cost of each component at the end of its service life (C_{RC}, \$). f_{RC} represents the scale factors, and $\mathrm{SSF}(i,N)$ corresponds to the sinking fund coefficients (%). The service life of the components is represented by N_{comp} (years), and CO_2^{tax} refers to the carbon tax (\$/tCO$_2$). The CO_2 coefficient for electricity purchase is denoted by λ (g/kWh). The electricity purchased from the grid is represented by E_{GP}^t (kWh), while E_{GS}^t denotes the electricity sold to the grid (kWh). TCO_2 represents the annual carbon emission (g/yr), C_{purch}^t is the cost of electricity purchased (\$/yr), and C_{sell}^t refers to the revenue from selling electricity (\$/yr). The remaining service life of the components is denoted by N_{rem} (years), and N_{rep} indicates the replacement service life of the components (years).

The optimization model calculates the NPC by summing the discounted cash flows at the end of each year. The annual cost is multiplied by the NPC using the CRF. The NPC at the end of the project's lifespan is given by Equation (34) [78]. Equation (34) defines the objective function for minimizing the NPC, which is derived from the ratio of the total annual costs to the CRF. The CRF depends on the annual real interest rate (i) and the project horizon (n). The annual real interest rate is calculated from the nominal interest rate (i') and the expected inflation rate (f).

$$\text{Minimize } NPC = \frac{C_{\mathrm{ann}}^{\mathrm{tot}}}{CRF(i,N)} \tag{34}$$

Furthermore, Table 5 presents the decision criteria and equations utilized in evaluating the optimization and feasibility results. The average cost per kWh of useful energy produced by the HPS is known as the cost of energy (COE). The renewable fraction (RF) refers to the proportion of total annual energy generated from RES that is transferred to the load. This fraction represents the ratio of RES to the load in the system. If the energy generated by the RES exceeds the load demand and the ESS is full, or if grid sales are limited, the electricity must be curtailed or excessed (CE or EE) as it is not used to service the load or charge the ESS [79]. Additionally, P_F denotes the difference between the PV power output (P_{PV}) and the combined demand of battery power and load power at time t, when the PV output exceeds the load demand (P_L). Similarly, P_G represents the difference between the load power demand and the combined output of PV and battery power at time t, when the load demand exceeds the PV output. The total PV power is calculated by integrating the power, subtracting the total feed-in power (P_F), and then dividing by the total PV power to determine the SCR [80]. In contrast, the SSR is calculated by subtracting the total electrical load from the total grid supply power (P_G) and dividing by the total electrical load. The SCR is determined by the ratio of power fed from the PV system to the load relative to the total PV production, while the SSR represents the proportion of grid supply power to the total load. The variables P_{GP} and P_{GS} represent the power purchased from and sold to the grid, respectively, while P_{load} refers to the served load. $E^{with;HPS}$ indicates the total electricity purchased from the grid when the HPS is used to supply the load, while $E^{only;grid}$ corresponds to the total electricity purchased in a system where the load is entirely met from the grid. $P_{curtailment}$ refers to the excess electricity that surpasses demand and cannot be sold due to grid sales constraints. Additionally, dt represents

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the time steps, typically one hour. Another critical metric is the EXR, which expresses the ratio of energy provided by the HPS ($E^{with;HPS}$) to the energy provided by the grid alone ($E^{only;grid}$) [81].

TABLE 5. Decision criteria

Metric	Formula	Metric	Formula
CO_2	$0.4261 \sum P_{GP}$	SCR	$\frac{\int P_{PV}\,dt - \int P_F\,dt}{\int P_{PV}\,dt}$
RF	$1 - \frac{\sum (P_{GP})}{\sum (P_{load})}$	SSR	$\frac{\int P_L\,dt - \int P_G\,dt}{\int P_L\,dt}$
EXR	$1 - \frac{\sum E^{\text{with HPS}}}{\sum E^{\text{only grid}}}$	CE	$\sum P_{curtailment}$

III. OPTIMIZATION RESULTS

The performance evaluation of energy systems under various tariff mechanisms and carbon pricing scenarios is of paramount importance for the effective integration and deployment of renewable energy technologies. This study provides a comprehensive comparative analysis of Net Metering (NM) and Net Billing (NB) schemes, detailed respectively in Table 6 for NM and Table 7 for NB, incorporating city-specific load profiles and examining the impacts of carbon taxation. A detailed assessment is conducted on how system sizing and cost-effectiveness parameters evolve as a result of the interplay between tariff policies and carbon costs.

The NM mechanism promotes rapid expansion of renewable capacity by compensating exported electricity at full retail rates. This approach facilitates RF up to 41% and SCR reaching 69% in cities where residential PV systems dominate, such as Antalya and Düzce. Nevertheless, because excess generation is credited at parity rates, NM can lead to reduced self-consumption rates and oversizing of systems, ultimately detracting from overall system efficiency. In commercial and industrial segments, PV-ESS hybrid systems are becoming prevalent; meanwhile, in wind-rich regions like Çanakkale, wind turbine–based systems that obviate the need for storage offer competitive alternatives with the lowest LCOE values (0.0206–0.0234 $/kWh) and minimal CO_2 emissions (0.59–0.66 tons/yr). The introduction of a 40 $/t$CO_2$ carbon tax under NM results in only marginal increases in PV capacity. For example, PV capacity in Antalya's residential sector rises modestly from 1.51 kW to 1.52 kW, whereas commercial loads experience a more substantial increase from 679 kW to 1085 kW. However, limited LCOE reductions and modest CO_2 abatements create complex effects on investment payback periods. In Antalya's residential sector, the discounted payback period (DP) decreases from 14.58 to 12.12 years after the carbon tax, whereas in the commercial sector, it increases from 9.12 to 10.49 years. These findings suggest that carbon taxation alone is insufficient as a strong incentive under prevailing market conditions.

The NB mechanism differentiates pricing between exported and consumed electricity, aligning system design more closely with consumption patterns and reducing the economic value of surplus production. This approach achieves high self-consumption ratios even without energy storage in the residential sector, for instance, 65.93% in Antalya and 60.87% in Isparta, thereby enhancing economic efficiency. Under carbon taxation, PV capacity increases more significantly than under NM (e.g., 1.60 kW to 2.12 kW in Antalya). While NB encourages PV capacity growth in commercial segments, ESS capacities remain stable, and self-consumption ratios slightly decline due to lower export prices (Antalya SCR decreases from 51.66% to 47.95%). In the industrial sector, NB supports high PV-ESS integration but imposes stricter economic discipline, requiring more careful design decisions. Wind-assisted systems in Çanakkale offer low-cost solutions with high self-consumption ratios (64.95%), yet carbon taxation substantially raises investment costs in high-demand areas (e.g., from 21.1 million $ to 24.5 million $) while delivering limited emissions reductions. Although LCOE values under NB are generally higher than those under NM, NB promotes localized consumption-oriented systems, which offers distinct advantages.

Carbon taxation generally yields modest increases in PV capacity and moderate reductions in CO_2 emissions. In Antalya, both NM and NB scenarios exhibit slight improvements in investment payback periods following carbon tax implementation. For example, DP in the residential sector under NB decreases from 17.31 to 15.51 years, whereas the industrial segment shows limited positive effects. Cities such as Çanakkale and Isparta respond differently due to variations in local resource potentials and load profiles; notably, regions with high wind potential benefit from reduced storage requirements and competitive, low-cost system alternatives.

Although carbon taxation yields notable environmental benefits, such as significant increases in renewable energy use and reductions in carbon emissions, it is equally important to consider the broader economic consequences of implementing such fiscal policies. In particular, the implementation of carbon taxes may contribute to increased electricity prices for end-users, especially in the absence of adequate subsidy mechanisms or market support. This could pose affordability challenges for residential consumers and small-scale enterprises, which are often less resilient to abrupt changes in utility costs. The financial strain resulting from such policy instruments may exacerbate existing energy poverty in vulnerable populations, potentially leading to public resistance or reduced political acceptance. Moreover, higher energy costs may negatively affect the competitiveness of energy-intensive industries, particularly in developing economies where industrial margins are narrower and global market competition is intense. In these contexts, carbon taxation may inadvertently discourage industrial growth or lead to carbon leakage, where companies relocate production to countries with laxer environmental regulations, thereby undermining global emission reduction efforts. The macroeconomic im-

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TABLE 6. Performance comparison across city, load type, and carbon tax scenarios (Net Metering)

Load	CT ($/tCO$_2$)	City	PV (kW)	WT (kW)	PCS (kW)	ESS (kWh)	NPC (M$)	LCOE ($/kWh)	DP (yr)	CE (%)	RF (%)	CO_2 (t/yr)	SCR (%)
Residential	0	Antalya	1.51	0.00	0.95	0	0.009	0.0413	14.58	0.60	41.50	1.15	68.42
		Çanakkale	0.00	2.00	0.00	0	0.007	0.0206	15.12	0.00	77.60	0.66	47.54
		Isparta	1.41	0.00	0.95	0	0.009	0.0409	13.91	0.50	41.60	1.15	69.46
		Düzce	1.58	0.00	1.08	0	0.009	0.0416	15.32	0.34	41.00	1.17	66.55
	40	Antalya	1.52	0.00	0.93	0	0.011	0.0512	12.12	0.75	41.60	1.15	68.22
		Çanakkale	0.36	2.00	0.23	0	0.008	0.0234	13.48	0.09	80.80	0.59	46.62
		Isparta	1.49	0.00	0.96	0	0.011	0.0501	11.80	0.81	43.00	1.13	67.00
		Düzce	1.60	0.00	1.01	0	0.012	0.0516	12.80	0.76	41.10	1.17	66.02
Commercial	0	Antalya	679	0	406	441	1.808	0.0334	9.12	1.49	75.50	117.68	65.99
		Çanakkale	321	200	215	0	1.196	0.0213	7.09	0.23	79.10	104.23	67.58
		Isparta	834	0	534	400	1.736	0.0268	9.97	1.57	82.70	99.32	54.06
		Düzce	672	0	406	434	1.913	0.0360	9.27	1.72	72.10	131.80	66.30
	40	Antalya	1085	0	659	393	2.010	0.0264	10.49	1.68	86.20	93.24	45.21
		Çanakkale	323	199	208	0	1.398	0.0250	6.42	0.04	70.00	104.35	67.61
		Isparta	1103	0	695	371	1.907	0.0237	10.40	1.97	87.70	87.66	42.59
		Düzce	848	0	521	433	2.150	0.0349	9.52	1.80	78.70	116.49	55.87
Industrial	0	Antalya	6799	0	4142	5779	21.125	0.0346	12.42	1.23	66.90	1793.18	49.26
		Çanakkale	0	3122	0	0	12.736	0.0217	7.48	0.00	68.70	1628.14	58.78
		Isparta	8880	0	5696	5684	20.414	0.0269	13.54	1.44	75.00	1685.73	37.38
		Düzce	6042	0	3659	6637	22.152	0.0397	12.16	1.51	61.30	1919.06	54.51
	40	Antalya	8047	0	4840	5714	24.516	0.0361	12.08	1.52	71.00	1743.82	42.68
		Çanakkale	0	3622	0	0	15.850	0.0247	7.52	0.00	72.90	1544.68	52.67
		Isparta	9067	0	5826	5577	23.649	0.0307	12.48	1.43	75.40	1684.28	36.64
		Düzce	7488	0	4617	5938	25.757	0.0407	12.13	1.52	67.30	1831.73	46.11

TABLE 7. Performance comparison across city, load type, and carbon tax scenarios (Net Billing)

Load	CT ($/tCO$_2$)	City	PV (kW)	WT (kW)	PCS (kW)	ESS (kWh)	NPC (M$)	LCOE ($/kWh)	DP (yr)	CE (%)	RF (%)	CO_2 (t/yr)	SCR (%)
Residential	0	Antalya	1.60	0	0.994	0	0.00996	0.04410	17.31	0.701	43.1	1140	65.93
		Çanakkale	0.806	1	0.509	0	0.00875	0.03427	16.47	0.255	68.6	711	65.63
		Isparta	1.72	0	1.11	0	0.00978	0.04149	17.12	0.916	47.2	1105	60.87
		Düzce	1.93	0	0.943	0	0.01018	0.04626	17.84	0.802	39.4	1183	68.45
	40	Antalya	2.12	0	1.30	0	0.01210	0.04816	15.51	0.966	51.3	1085	54.21
		Çanakkale	0.794	2	0.503	0	0.00990	0.02726	15.98	0.174	83.6	528	44.88
		Isparta	2.27	0	1.46	0	0.01185	0.04464	15.45	1.060	55.2	1054	49.81
		Düzce	1.94	0	1.21	0	0.01241	0.05184	15.72	0.999	46.7	1131	58.04
Commercial	0	Antalya	925	0	566	393	2.40308	0.03575	11.93	1.480	83.1	100729	51.66
		Çanakkale	517	267	316	163	2.74169	0.02926	11.00	0.813	90.3	60943	53.85
		Isparta	938	0	599	379	2.28039	0.03216	11.72	1.670	85.0	94278	48.93
		Düzce	920	0	576	407	2.60783	0.03984	12.48	1.610	80.6	112700	52.21
	40	Antalya	1013	0	617	402	2.59229	0.03600	11.22	1.600	85.0	96086	47.95
		Çanakkale	545	286	329	168	2.17991	0.02940	10.14	0.914	91.3	57046	51.31
		Isparta	1016	0	664	412	2.45681	0.03247	11.04	1.400	86.6	89700	45.89
		Düzce	989	0	612	418	2.82045	0.04098	11.61	1.820	82.2	108652	49.34
Industrial	0	Antalya	6463	0	3930	5660	24.27482	0.04099	13.31	1.200	65.5	1814752	51.25
		Çanakkale	2541	2205	1530	3430	20.06751	0.03580	11.13	0.507	76.0	1194077	64.95
		Isparta	6622	0	4218	5830	23.43917	0.03773	13.17	1.350	68.0	1760767	48.28
		Düzce	6427	0	3930	5863	25.67159	0.04445	13.91	1.470	63.2	1887615	52.14
	40	Antalya	7120	0	4334	5773	27.72007	0.04415	12.45	1.280	68.0	1778408	47.40
		Çanakkale	2850	2459	1679	3522	22.29936	0.03699	10.35	0.676	78.8	131921	59.55
		Isparta	7055	0	4502	0	26.81662	0.04144	12.16	1.380	69.6	1742880	46.86
		Düzce	6838	0	4253	6000	29.27637	0.04886	12.84	1.330	65.0	1861033	49.71

plications can also extend to inflationary pressures, shifts in employment patterns, and changes in trade balances, particularly for countries reliant on fossil fuel exports. For carbon taxation to yield a net positive effect, it is therefore essential to embed such policies within a broader socio-economic framework that includes compensatory measures. These may include targeted subsidies for low-income households, transitional support for affected industries, investment in clean energy infrastructure, and incentives for innovation and energy efficiency. Furthermore, phased implementation strategies, adaptive tax rates, and regional flexibility can help accommodate local economic conditions and institutional capacities. International cooperation and financial assistance mechanisms, particularly for least developed countries, can also play a crucial role in enhancing the feasibility and fairness of carbon pricing policies on a global scale. In this regard, while carbon taxation serves as an effective environmental policy tool, its successful adoption in developing regions requires complementary and context-sensitive measures to ensure that ecological gains are achieved without compromising economic stability or social equity. Only through a holistic and inclusive approach can carbon taxation deliver on its dual promise of climate action and sustainable development.

Figure 2 presents a comparative assessment of the technical and economic performance of NM and NB mechanisms under varying carbon tax scenarios. The imposition of a carbon tax at 40 $/tCO$_2$ results in a significant increase in PV

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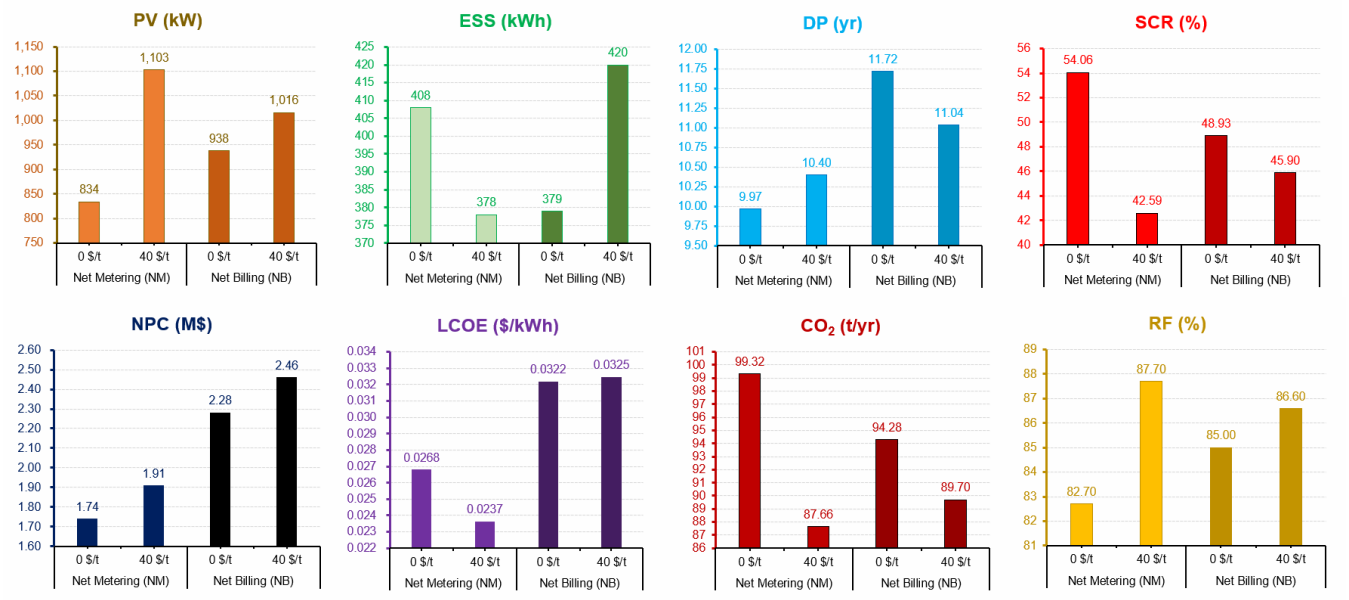


FIGURE 2. Comparison of Net Metering and Net Billing under Carbon Tax Scenarios (Isparta-Commercial Load)

capacity by approximately 32.4% for NM and 8.3% for NB. Regarding ESS capacity, NM experiences a slight decrease of 7.4%, whereas NB demonstrates an increase of 10.8%, indicating stronger storage integration under the NB scheme in response to carbon pricing. The NPC rises by 9.8% for NM and 7.9% for NB. LCOE decreases by 11.6% under NM, while it slightly increases by 0.9% under NB. RF improves by 6.0% for NM and 1.9% for NB, accompanied by reductions in CO_2 emissions of 11.7% for NM and 4.9% for NB. The DP slightly lengthens by 4.3% for NM, whereas it shortens by 5.9% for NB. The SCR decreases markedly by 21.2% under NM, compared to a moderate 6.3% decline under NB. PCS capacity increases by 30.2% for NM and 10.9% for NB. Overall, these results indicate that carbon taxation promotes renewable capacity expansion and environmental benefits across both mechanisms; however, NM systems tend to offer greater cost-effectiveness and operational efficiency, while NB systems encourage enhanced economic discipline and storage integration. This analysis highlights the complex, mechanism-dependent impacts of carbon pricing on distributed energy resource design and investment decisions within distinct tariff structures.

The comparative analysis of NM and NB mechanisms reveals significant differences in renewable capacity expansion, system efficiency, and investment payback periods. NM enables rapid capacity growth but can lead to oversized systems and low self-consumption rates, thereby increasing long-term grid dependency and flexibility requirements. In contrast, NB enforces economic discipline by pricing exports lower, encouraging consumption-aligned, high self-consumption systems, albeit with more conservative capacity growth. Carbon taxation alone has limited efficacy and should be complemented with dynamic pricing, demand response programs, and grid flexibility policies to effectively accelerate renewable investments. As evidenced by the Çanakkale case, differentiated and locally tailored incentive mechanisms in regions with abundant renewable resources outperform uniform national policies in both effectiveness and cost-efficiency. In conclusion, NM and NB schemes should be considered complementary, with carbon taxation serving as a supportive element integrated alongside other policy instruments. These combined approaches are essential for Türkiye to achieve its distributed renewable energy targets and optimize grid integration.

IV. SENSITIVITY OF HYBRID SYSTEMS TO TARIFF STRUCTURES AND CARBON TAX

A sensitivity analysis was conducted assuming a carbon tax ranging from 0 to 100 \$/tCO_2 and increasing grid electricity purchase prices using multipliers from 1.0 to 2.0. This analysis was motivated by rising global environmental concerns driving the phased implementation of carbon taxation policies. Furthermore, although electricity tariffs are currently subsidized by governments in countries such as Türkiye, these subsidies are expected to decline in line with national clean energy transition objectives. Potential increases in electricity procurement costs due to market volatility were also considered.

Sensitivity analyses evaluating the performance of hybrid energy systems operating under the net billing mechanism revealed the significant influence of economic-parametric thresholds on system component optimization. Under net billing conditions, where the export price of surplus electricity to the grid is lower than the import price, the importance of strategies aimed at increasing self-consumption rates becomes markedly pronounced. Results indicate that

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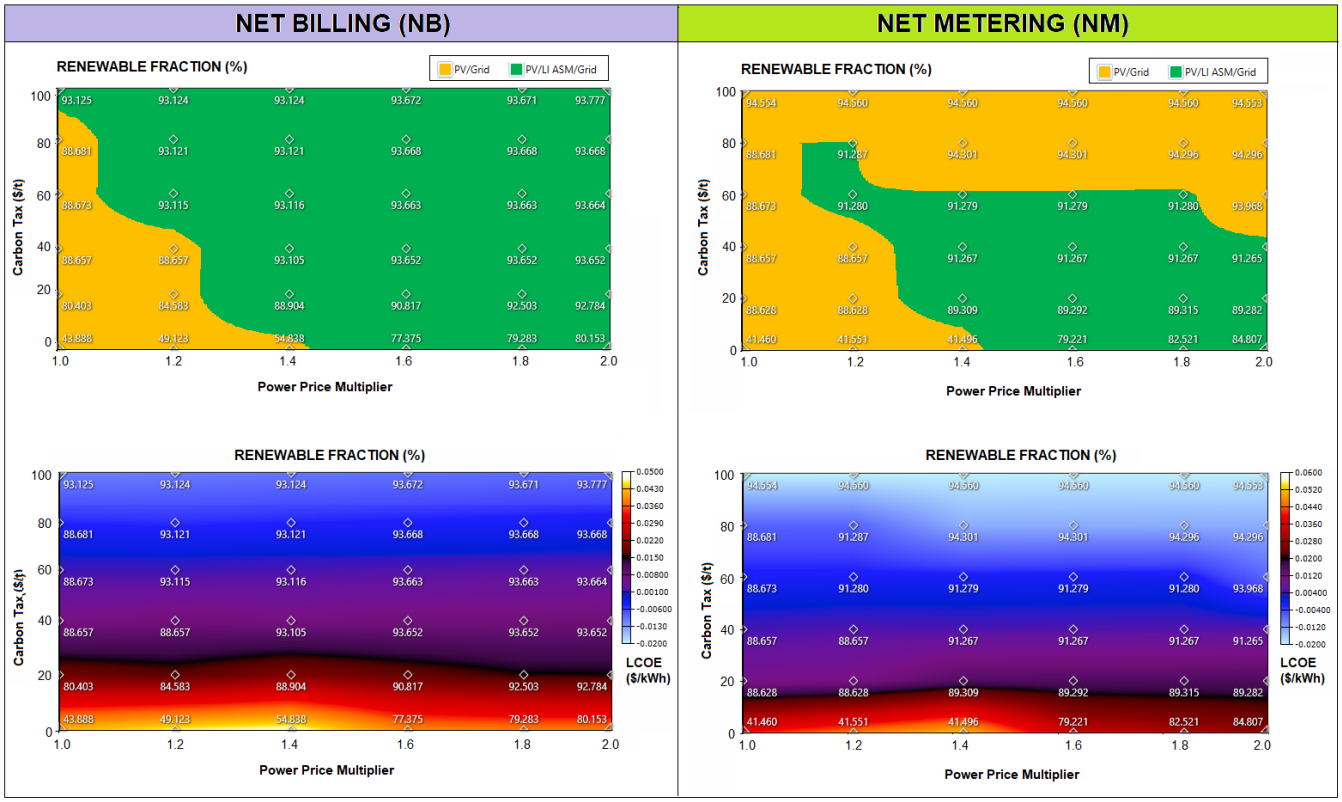


FIGURE 3. Hybrid system optimization under varying carbon tax and tariff schemes

when the power price multiplier reaches 1.4, the PV installation capacity increases substantially from 1.66 kW to 12 kW. However, for this capacity increase to be economically viable, integration with battery storage systems is essential. Otherwise, clipped energy rates rise to 15–20% due to insufficient inverter capacity, leading to considerable production losses and reduced economic efficiency. Within the net billing framework, aggressive PV capacity expansion occurs alongside high grid electricity prices, but the low export price makes energy storage economically imperative. Consequently, battery investments become critical not only technically but also economically. CO_2 penalty scenarios further clarify this economic transition; from approximately 40–50 \$/tCO_2 onward, battery integration becomes rational both from a system cost and environmental performance perspective. Beyond this threshold, battery throughput and storage durations increase significantly, demonstrating carbon pricing as a catalyst for accelerating storage investments under net billing. Additionally, scenarios with high PV production during peak hours often face inverter capacity constraints, leading to diminished overall system performance and elevated clipped energy values. This underscores the necessity of optimizing not only PV capacity but also inverter and battery sizing simultaneously. Thus, net billing emphasizes the importance of infrastructure investments that enhance system flexibility, highlighting that energy policies should address the entire system rather than focusing solely on installation incentives.

In summary, detailed analyses under net billing highlight that:

- Increasing the self-consumption ratio is critical for system economics,
- The PV-to-battery ratio must be carefully balanced,
- Carbon pricing and grid tariffs can play a pivotal role in stimulating battery investments.

These findings suggest that policymakers should extend renewable energy support beyond installation subsidies to include battery incentive programs and flexible tariff structures that promote self-consumption. Such comprehensive approaches can render net billing-based systems more sustainable economically and environmentally.

Sensitivity analyses investigating the impact of the net metering mechanism on hybrid energy systems demonstrate a high dependency of renewable energy integration, especially PV, battery utilization, and grid interaction on macroeconomic policy parameters such as the energy price multiplier, carbon emission penalties, and grid electricity unit costs. The findings reveal that upon reaching a carbon penalty threshold of approximately 20 \$/tCO_2, transitions toward PV-battery systems commence, marking a critical inflection point in decarbonization pathways. As carbon penalties increase, both PV capacity and battery storage expand, while grid energy imports decline. However, at carbon prices approaching 100

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$/tCO_2$, high capital costs of PV and battery systems can dominate economically, occasionally resulting in negative internal rate of return (IRR) and diminishing return on investment (ROI).

At energy price multipliers of 1.6 and above, the system becomes fully PV and battery-based, minimizing grid dependency and achieving renewable penetration above 90%. In particular, at a 1.6 energy price multiplier, the threshold for battery adoption falls within the 20–40 $/tCO_2$ range, triggering substantial increases in battery capacity and inverter sizing. These enhancements improve system flexibility while markedly reducing energy exchanges with the grid. When PV capacity reaches approximately 28 kW, the system's annual energy production approximates 38 MWh, fully covering annual consumption and increasing grid feed-in. In scenarios with active net metering, the ability to sell excess energy to the grid further enhances economic efficiency and environmental sustainability. Conversely, scenarios lacking net metering or carbon penalties demonstrate limited battery integration and sustained grid reliance, negatively impacting both environmental performance and autonomy. The lowest total system cost and LCOE are attained in scenarios optimizing PV capacity without carbon penalties; however, CO_2 emissions remain high, and the system's carbon footprint is not substantially reduced.

Based on these findings, the following key policy recommendations emerge:

- Elevating carbon pricing beyond a critical threshold (approximately 20 $/tCO_2$) improves the economic attractiveness of PV and battery investments, accelerating the transition to low-carbon energy systems.
- Increasing energy price multipliers in conjunction with net metering facilitates the proliferation of grid-independent, high-renewable penetration systems.
- Integrated application of net metering and carbon pricing incentivizes investors and supports sustainable energy transitions.
- Hybrid system design must be responsive to macroeconomic parameters such as carbon prices, grid electricity costs, and energy policies, treating these as strategic levers in system optimization.

In this context, supporting net metering with robust carbon pricing not only maximizes economic efficiency but also enhances environmental sustainability and energy system flexibility.

Sensitivity analyses distinctly reveal the contrasting impacts of net metering and net billing mechanisms on the performance of hybrid renewable energy systems. Net metering enables consumers to sell self-generated electricity to the grid at the same rate as consumption, maximizing PV generation, significantly reducing the system's carbon footprint, and achieving high renewable penetration. Particularly under carbon pricing scenarios, net metering yields highly attractive economic outcomes, including negative NPC and low LCOE. Conversely, in net billing, the lower export price limits PV capacity expansion, elevates the criticality of battery investments, and extends economic payback periods. This increases grid electricity purchases, undermining system autonomy and environmental performance. Accordingly, energy policy design should recognize that net metering more strongly incentivizes renewable investments in the short to medium term, while net billing provides a more financially sustainable model for long-term system balance and grid reliability. Policymakers are encouraged to dynamically and flexibly integrate these two mechanisms, employing carbon pricing, electricity export/import tariffs, and grid access fees as policy levers to foster hybrid models that incentivize both investors and system operators.

V. POLICY MECHANISM COMPARISON

In previous work focusing on second-life battery systems without wind turbines [55], a comprehensive comparison of energy policies, including investment subsidies, carbon taxes, net metering, net billing, and feed-in tariffs, was conducted, highlighting their individual and hybridization potentials in the Turkish energy market. In contrast, the present study concentrates on the feasibility of implementing net metering, net billing, and carbon taxation within wind-integrated systems using fresh batteries, across varied geographical settings and demand profiles.

Among the three policies examined, net metering offers the most direct economic benefit for prosumers by crediting excess generation at retail rates, yet it may challenge the long-term financial viability of utilities due to reduced revenue recovery. Net billing, by compensating exports at wholesale or avoided cost rates, provides a more sustainable balance between consumer incentives and grid operator needs. Carbon taxation, meanwhile, differs fundamentally in approach: rather than altering pricing structures for distributed generation, it imposes costs on carbon emissions, promoting broader decarbonization, but potentially leading to higher electricity prices in the absence of supportive regulatory mechanisms. From a technical standpoint, both net metering and net billing rely on bi-directional metering infrastructure and are relatively easy to integrate into existing grid frameworks. Net billing, however, grants utilities greater control over power flows and demand-side balancing due to its pricing independence from consumption. In contrast, carbon taxation does not affect technical operations directly but influences long-term system evolution by incentivizing cleaner generation technologies through economic signals.

In terms of economic viability, net metering ensures maximum short-term returns to prosumers, though at the risk of destabilizing utility cost recovery models, especially as distributed generation grows. Net billing, by aligning export compensation with market realities, enhances economic sustainability while preserving investment incentives. Carbon taxation generates government revenue and internalizes environmental costs but can exert inflationary pressure on electricity prices, which may require mitigating policies such as subsidies or revenue recycling to ensure affordability and

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equity.

From an environmental perspective, carbon taxation emerges as the most impactful instrument, directly discouraging carbon-intensive generation and accelerating the transition to cleaner sources. Net metering and net billing also support renewable deployment, but their environmental benefits are more localized and dependent on implementation parameters (e.g., system size limits, compensation schemes). In this light, hybrid policy designs, such as combining carbon taxes with net billing, may achieve greater synergy, enabling both systemic decarbonization and distributed energy expansion.

Ultimately, the effectiveness of each policy depends on regional objectives, grid capacity, and socio-economic context. This study, grounded in Türkiye's diverse climatic and demand conditions, contributes actionable insights for designing balanced, region-specific policy frameworks that support both environmental goals and energy market resilience.

VI. DISCUSSION

This study contributes to the growing body of research on HRES by evaluating the combined effects of geographical diversity, consumer demand types, carbon taxation, and metering policies within the context of Türkiye's energy landscape. The comparison with existing literature reveals both alignment and divergence with earlier findings, particularly in how real-world policy instruments influence system design, cost-effectiveness, and environmental outcomes.

A consistent theme across prior studies is the positive impact of carbon taxation on both emissions reduction and system efficiency. For instance, [82] and [83] demonstrate that increasing carbon taxes or prices leads to improved environmental performance and promotes greater adoption of renewable sources. These outcomes are in strong agreement with the findings of the current study, where a 40 $\$/tCO_2$ carbon tax enhanced renewable fraction by 32% and reduced LCOE by 11.75%. However, unlike studies such as [82], which incorporate sophisticated multi-objective optimization methods (e.g., DEA, robust stochastic models), the present work relies on predefined scenario-based simulation using HOMER Pro. This methodological choice, while less exploratory in terms of optimization frontier discovery, provides a practical and replicable tool suitable for policy-focused evaluations in real-world settings. Moreover, several studies including [84]–[86] emphasize the importance of location-specific system design, reinforcing the current study's conclusion that wind-abundant cities like Çanakkale provide optimal conditions for hybrid deployment. The referenced case on Faial Island [85], for example, showcases how localized wind variability influences storage sizing and system configuration, echoing this study's emphasis on Çanakkale's wind superiority as a key driver of reduced NPC and LCOE. Unlike [86], which integrates microhydropower and floating PV for agricultural systems, this study targets urban and commercial applications, further diversifying the spectrum of practical use cases.

When it comes to billing mechanisms, the literature indicates a broad consensus that net metering offers more favorable outcomes for economic feasibility compared to net billing or zero-export policies. Studies such as [87]–[89] consistently report that net metering reduces payback periods and supports higher levels of renewable self-consumption, consistent with the 22% cost advantage observed in this study. Notably, while some works such as [90] highlight net billing's viability for large-scale industrial installations under specific market conditions, the current research underscores that for wind-rich commercial settings in Türkiye, net metering provides superior outcomes, especially in reducing dependency on grid electricity and increasing financial returns.

From a scope and policy integration perspective, this study distinguishes itself from works like [14], [91], [92], which either focus heavily on thermal or CHP integration or adopt life-cycle assessment techniques. While these methods offer valuable insights into energy system performance from broader environmental or thermodynamic viewpoints, they often exclude the regulatory or billing structures that define real-world feasibility. In contrast, this study anchors its analysis within Türkiye's policy framework, evaluating metering and taxation scenarios not as theoretical tools but as active levers shaping system performance. Furthermore, the incorporation of consumer diversity (residential, commercial, industrial) and regional climate variation across multiple cities expands upon the mostly single-site or mono-sector approaches in the literature. For instance, unlike [93] and [94], which limit their scope to residential rooftop PV or net billing only, this research evaluates sector-specific implications, uncovering nuanced differences such as commercial users benefiting disproportionately from wind resources under net metering. Finally, several referenced studies ([95], [96]) advocate for energy autonomy and localized energy communities, a direction compatible with the policy recommendations of this study. However, the current work advances the discussion by quantifying how specific regulatory tools such as carbon taxation and net metering interact with technological configurations in measurable ways (e.g., reductions in LCOE, SP, and emissions), offering a quantitative basis for policy calibration. In summary, this study confirms and extends the current knowledge base by providing a comprehensive, multi-scenario, and policy-aware analysis of hybrid systems. While its approach is grounded in Türkiye's context, the framework holds transferable relevance to other emerging markets seeking to balance energy security, affordability, and sustainability. Future work should build on this foundation through field validation, dynamic tariff modeling, and expanded geographic coverage to better inform national and regional energy transition strategies.

VII. CONCLUSIONS

This study presents a comprehensive evaluation of hybrid renewable energy systems (HRES) within Türkiye's diverse climatic and socio-economic context, analyzing 48 scenario-based simulations across distinct regions and consumer seg-

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ments. The findings highlight the superior performance of net metering (NM) over net billing (NB) in accelerating renewable capacity expansion, particularly for commercial users in wind-rich regions. While Çanakkale demonstrates strong wind potential, Antalya benefits from consistent solar irradiance, Isparta offers a balanced renewable mix, and Düzce highlights the challenges of limited resource availability, requiring targeted incentives such as improved storage support or grid modernization. These region-specific insights emphasize that no single policy framework is universally optimal, and localized hybrid strategies are essential for maximizing HRES effectiveness across Türkiye. Conversely, NB promotes greater economic discipline, higher self-consumption rates, and enhanced battery integration, especially when combined with carbon pricing. Under NB, battery systems become economically viable when carbon prices exceed approximately 40–50 $/tCO$_2$, while under NM this threshold drops to around 20 $/tCO$_2$, indicating that pricing schemes significantly influence investment triggers. Notably, a carbon tax of 40 $/tCO$_2$ improved the renewable energy share by 32% and reduced the levelized cost of energy (LCOE) by 11.75%, demonstrating the dual economic and environmental benefits of fiscal instruments when properly calibrated. Sensitivity analyses further reveal that carbon pricing alone is insufficient without complementary tariff reforms and incentive mechanisms. Especially in NB scenarios, battery storage economics improve markedly beyond specific grid tariff and carbon penalty thresholds, while NM systems risk oversizing and diminishing returns at higher carbon costs. These outcomes underline the need for integrated, flexible policies that align technical design with economic and environmental objectives.

Finally, the study highlights that carbon pricing and metering mechanisms not only affect technical system performance but also directly shape investment behavior and system architecture. For emerging economies like Türkiye, policy frameworks must be carefully structured to balance environmental ambition with affordability and equity. Instruments such as targeted subsidies, transitional support programs, and regionally adaptive pricing models can mitigate the economic burden on vulnerable consumers and unlock broader public acceptance. Future research should validate these insights with empirical data, explore synergistic policy mechanisms, and consider evolving technology costs to enhance real-world applicability. Ultimately, a successful, equitable energy transition in Türkiye and comparable emerging economies hinges on integrating policy design with technical optimization and regional specificity. This work provides actionable guidance for policymakers, investors, and planners aiming to scale renewable energy deployment effectively.

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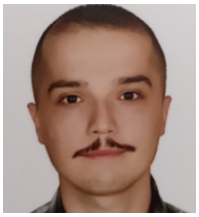
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This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2025.3587879



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