IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 27 September 2023, accepted 9 October 2023, date of publication 13 October 2023, date of current version 18 October 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3324547

RESEARCH ARTICLE

Optimal Sizing and Techno-Economic Evaluation of Microgrids Based on 100% Renewable Energy Powered by Second-Life Battery

ALPASLAN DEMIRCI
Department of Electrical Engineering, Yıldız Technical University, 34220 İstanbul, Turkey
e-mail: ademirci@yildiz.edu.tr

ABSTRACT The rapid development of distributed renewable energy has made energy storage essential for demand reliability and flexible energy management. Due to the high investment costs of fresh batteries (FB), achieving a positive and efficient economy takes work. However, second-life batteries (SLB), whose capacity decreases by 20-30% after the first use, can be preferred as alternative energy storage to overcome this challenge. This paper investigates the renewable potential of shared energy storage and the feasibility of FB&SLB for prosumers. In addition, threshold points are determined by examining the financial obligations associated with an increasing share of renewables on the path to 100% renewable energy. Moreover, the impact of carbon taxes on extra CO_2 reduction costs is assessed depending on the carbon quota. The results confirm the superiority of SLB, which increases throughput by 11.5% while reducing CO_2 by 9.4%. Renewable fractions (RFs) above 59.2% and 87% in optimal hybrid power systems (HPS), in different climate potentials, and for low and high energy tariffs lead to costly investments. Increasing the carbon tax could reduce the cost of CO_2 reduction by up to 5.2 \$/kg in the early stages of carbon limits while avoiding extra costs of up to 2.1 \$/kg for FB at lower CO_2 limits. In contrast, increasing RF from 95% to 100% would increase net present cost (NPC) by up to 122.65%. It will be more critical than ever for governments to support prosumers' financial trade-offs in the transition to clean energy.

INDEX TERMS Carbon emission, carbon tax, energy storage, renewable energy, second-life battery.

NOMENCLATURE

A	Coefficient fit in the DOD.
A_{PV}	Area of the PV panel (m^2).
c	The storage capacity ratio.
$C_{ann,tot}$	Total annualized cost (\$/yr).
$C_{buy}(t)$	Cost of purchasing electricity at t time (\$).
C_{cap}	The capital cost of the current system (\$)
$C_{cap}(\ell)$	The cost price of equipment ℓ (\$).
$C_{cap,ref}$	The capital cost of the base (reference) system (\$).
C_{GP}	Cost of purchasing electricity (\$).
C_{GS}	Income from selling electricity (\$).
C_i	Nominal annual cash flow for the current system (\$).
C_{inv}	Initial investment cost (\$).
$C_{i,ref}$	Nominal annual cash flow for reference system (\$).
C_{main}	Maintenance cost (\$).
$C_{sell}(t)$	The income from selling electricity at t time (\$).
C_{tax}	Carbon tax (\$).
CO_{tax}	Carbon tax factor (\$/t).
$CRF(i, N)$	Capital recovery factor (%).
d_0	The constant term in quadratic fit.
d_1	Coefficient of temperature in quadratic fit.
d_2	Coefficient of temperature squared in quadratic fit.
D	Exponential coefficient.
D_i^{β}	Exponent fit in the DOD.
E_{EE}	Total excess electricity (kWh/yr).

The associate editor coordinating the review of this manuscript and approving it for publication was Khmaies Ouahada.

$E_{ESS}(t)$	Energy-charged and discharged at time t (kWh).
E_{EV}	EV load energy (kWh/yr).
E_{gen}	Total energy generated (kWh/yr).
$E_{GP}(t)$	The electricity purchased from the grid at t time (kWh).
$E_{GS}(t)$	The electricity sold to the grid at time t (kWh).
E_{load}	The prosumer energy (kWh/yr).
E_{loss}	Total energy losses in HPS (kWh/yr).
E_{nonren}	The conventional energy source (kWh/yr).
E_{RES}	Total RES generation (kWh/yr).
E_{RES}^{cons}	Annual RES energy transferred to demand (kWh/year).
E_{served}	Total electrical load served (kWh/yr).
EE	Excess energy (%).
f	The expected inflation rate (%).
f_{PV}	PV derating factor (%).
$G_T(t)$	The solar radiation in time t (kW/m^2).
$G_{T,STC}$	The incident radiation at STC (kW/m^2).
I	Battery current (A).
I_{max}	The storage's maximum charge current (A).
i	Annual real interest rate (%).
i'	Nominal interest rate (%).
$IC(l)$	The ℓ equipment capacity.
k	The storage rate constant (h-1).
k_t	The time-and-temperature degradation constant.
ℓ	HPS equipment.
$LCOE$	Levelized cost of energy ($/kWh).
n	The life of the equipment.
N	Project lifetime (year).
N_{batt}	The number of batteries in the storage bank.
NPC	Net present cost at project time ($).
$P_{AC}(t)$	AC operating power of the PCS in t time (kW).
$P_{ch}(k)$	ESS's charging power (kW).
$P_{DC}(t)$	DC operating power of the PCS in t time (kW).
$P_{dch}(k)$	ESS's discharging power (kW).
$P_{ESS}(t)$	The power output of ESS at time t (kWh).
$P_{inv}(t)$	The power output of the inverter in t time (kW).
P_{out}	The output power of the battery (W).
$P_{PCS}(t)$	Converter power output in t time (kW).
$P_{PV}(t)$	PV panel output power in t time (kW).
$P_{rec}(t)$	The power output of the rectifier in t time (kW).
Q	The beginning total energy in the storage (kWh).
Q_1	The beginning available energy in storage (kWh).
Q_{max}	The total capacity of the storage bank (kWh).
R_0	The series resistance of the battery (Ω).
RF	Renewable energy fraction (%).
ROI	Return on investment (%).
α_c	The storage's maximum charge rate (A/Ah).
α_P	Temperature coefficient of power (−0.485%/°).
SCR	Self-consumption rate (%).
$SOC(t)$	Initial SOC of ESS (%).
$SOC(t+1)$	ESS's state of charge (%).
SSR	Self-supply rate (%).
T	The temperature of the storage bank (°C).
$T_a(t)$	Ambient temperature in t time (°).
$T_C(t)$	The PV cell temperature (°C).
$T_{C,STC}$	PV cell temperature under STC (25°).
TCO_2	Annual carbon emission (g).
$T_{NOCT}(t)$	Normal operation temperature in t time (°).
V_{nom}	The storage's nominal voltage (V).
V_0	The battery nominal voltage (V).
Y_{PV}	The rated PV capacity under STC (kW).
$\eta_{AC/DC}$	DC/AC conversion efficiency of the PCS (%).
$\eta_{batt,rt}$	The battery round-trip efficiency (%).
η_{ch}	The efficiency of charge cycles (%).
η_{dch}	The efficiency of discharge cycles (%).
η_{inv}	Inverter efficiency of the PCS (%).
η_{PV}	Maximum efficiency of the PV panels (%).
η_{rec}	Rectifier efficiency of the PCS (%).
ε	The maintenance factor of the equipment.
λCO_2	coefficient (968 g/kWh).
Δt	The length of the time step (hr).

I. INTRODUCTION

Clean energy alternatives are becoming increasingly popular to address rising global warming due to conventional sources, considering diminishing fossil reserves and increasing energy consumption. The renewable energy market, whose share in electricity supply is expected to increase by 1.4% per year in line with carbon neutrality policies [1], [2], is expected to grow further with reformed tax mechanisms [3], [4], [5]. Renewable energy sources (RES) caused an intermittent energy generation profile and increased curtailed energy, especially in higher capacity installations. Therefore, power quality problems in the distribution system cannot be dealt with. Accordingly, 100% of the RF potential was investigated regarding the penetration of renewables and battery technologies [6]. Thus, integrating lithium-based energy storage systems (ESS) with RES is essential to provide a sustainable energy supply in a reliable supply-demand match. Optimal ESS capacities maximize the potential RES benefit by considering power constraints on the grid [7] and serve zero carbon targets by reducing grid dependency [8]. It also provides flexibility for the grid [9], [10] and lowers amortization periods caused by extra costs in grid operation [11], [12]. It also smooths electricity generation profiles for RES [17], reduces the use of diesel fuel [13], and increases the probability of load cover ratio and self-consumption rate [14].

However, batteries increase carbon emissions [15] and lead to unnecessary water consumption in new production [16], [17]. At the same time, high investment costs in ESS applications risk climate crisis targets [18], [19], [20], [21]. In this context, electric vehicles (EV), which are growing in popularity in clean transportation and energy, may be promising for ESS applications. Due to increased internal impedance, EV batteries with reduced performance and capacity may not provide user satisfaction for transportation but may have a second life in stationary ESS applications. In the case of hybrid power systems (HPS), second-life EV batteries (SLB) have often been proven to provide many technical, economic, and environmental benefits. SLB can lower carbon footprint by up to 17% [22], reduce global warming potential by up to 16.2% [23], and increase self-sufficiency rates in behind-the-meter applications in energy communities by up to 3% [24]. It can also increase revenues by up to 77% [25] by reducing peak-time energy by 39% [26]. SLB benefits many stakeholders, extending EV battery life by up to 35% [27] and postponing potential environmental pollution from battery recycling [28].

SLB reduces the energy cost [29], [30] and total system costs [31] caused by the fresh battery (FB), significantly eliminating grid dependency [32] and compensating for environmental pollution [33], [34]. Although SLB advantages are often proven, many reasons cause uncertainty in their utilization, such as the complexity in determining residual capacity, the lack of proper selection of the stationary ESS application area based on the SLB profile, the absence of aging data history, the variability of the preparation process for a second life, and heterogeneous forms of cell chemistry. Without an international standard, it is widely accepted that governments should introduce appropriate incentive programs. However, there is a common misconception that reforms in environmental and energy taxes will increase the potential for renewable energy [35]. Previously, higher battery investment costs had to be subsidized due to low energy prices [36]. In contrast, today, subsidies, feed-in tariffs, and integration strategies are considered sufficient to increase the feasibility of batteries [37]. It also provided grid parity for residential photovoltaic panel (PV) capacities higher than 3 kW in cities with higher energy prices [38]. However, inappropriate subsidy policies may lead to inefficient HPS design and operation [39]. Also, subsidies may not be necessary at low latitudes and modest electricity prices [40], [41]. On the other hand, the carbon tax is gradually increased to achieve long-term climate targets. For instance, a 1 €/ton increase in the carbon tax could reduce CO_2 by 20.7% in the long term [42] and 11.58 kg/year per capita in the short term [43]. Although there are many potential benefits, such as up to 14% increase in the renewable fraction (RF) [44], the possible reduction in power purchase prices decreases the carbon tax benefit [45]. In addition, an inappropriate carbon tax may not achieve economic balance among stakeholders [46], [47]. Policymakers also should keep the carbon tax at a fair threshold to sustain active parallel exchange among energy communities [48], [49]. They are keeping the carbon tax below 83 \$/tonne.CO_2-eq [50] or keeping the free CO_2 quota below 50% could create public opinion in favor of HPS [51]. The gradual reduction of carbon emissions via carbon quotas reduces the financial benefit to prosumers by increasing capacity installations. Therefore, governments need to improve their subsidies in response to the altruism of prosumers [52], [53].

A. MOTIVATION AND CONTRIBUTIONS

Subsidy studies evaluating carbon policies and renewable potential for FB and SLB used in HPS in economic aspects are shown in Table 1. However, none of the studies have simultaneously evaluated the relevant optimization criteria such as carbon tax [54], [55], renewable potential [24], [33], [34], [54], [55], [56], [57], [58], [59], carbon reduction cost [54], [55], [58], [59], inflation and discount rate [33], [34], [54], [58], [59], [60]. Similarly, technical, economic, and environmental feasibility of FB and SLB used in HPS were not assessed simultaneously and comparatively in the recent optimization studies. Furthermore, how a leveled carbon tax could affect carbon reduction costs and improve the financial welfare of prosumers with the help of FB or SLB towards 100% renewable energy targets has not been analyzed in depth. Moreover, other shortcomings include evaluating ESS performance in short periods and underestimating ESS degradation due to temperature, charge-discharge power, and depth of discharge (DOD).

This study performs technical, economic, and environmental comparative feasibility analyses of HPS with FB and SLB used as an optimally sized shared ESS. In addition, the impact of gradual RF increase on the feasibility of HPS with SLB is evaluated under different climate potential and economic conditions considering a levelized carbon tax towards 100% renewable energy. Moreover, the impact of a carbon tax on CO_2 reduction costs determined at maximum CO_2 limits is analyzed. This paper also evaluates the impact of carbon tax on CO_2 reduction costs based on maximum CO_2 limits and fills the gap in the literature. However, technical aspects such as power quality issues in the distribution network are not included, as the focus is on the optimal sizing for the minimum cost and the evaluation of feasibility.

The main contributions of this study are as follows:

- Compared to FB, SLB can increase throughput by 11.5%, reduce CO_2 by 9.4% and shorten the payback period by 2.21 years.
- The renewable fractions for optimal feasibility in Spain, England, and Türkiye are %87, %82.44, and %59.2.
- The capacity increase in SLB required to increase the RF from 85% to 95% is less than 30%, while to increase the RF from 95% to 100% is 221%.
- The prosumer cost increases due to lower carbon quotas for the optimum threshold point are 2.5-16 \$/kg.

TABLE 1. Comparison of related studies regarding sensitivity analyses.

Ref.	Location	Optimal Sizing		Sensitivity				Aim	Finding
		FB	SLB	CT	RP	CER	IR&DR		
[24]	Italy		✓		✓			Demand response analysis of the SLB-based HPS to increase energy independence	Combining subsidies and self-consumption can reduce the payback period by up to 5 years.
[33]	Detroit, Los Angeles, New York, Phoenix, Portland, US	✓	✓		✓		✓	The technical, economic, and environmental analysis of SLB-based HPS for EV fast charging in different US	Levelized cost of electricity (LCOE) was reduced by 12-41% and global warming by 7-77% compared to FB.
[34]		✓	✓		✓		✓	Investigation of the benefit of SLB in rooftop PV grid services	Advantages in grid service as LCOE and CO_2 are reduced by up to 57% and 31%, respectively, compared to FB.
[54]	Germany, Spain, England			✓	✓	✓	✓	Assessing the effectiveness of climate policies by subsidizing renewable resources against carbon pricing or emission reductions	The marginal reduction cost of CO_2 in Germany is 41 €/ton, while in England, it is 36 €/ton.
[55]	Guangdong, China			✓	✓	✓		Analyzing the impact of carbon pricing and renewable energy subsidies on the direct cost of electricity generation	Reducing carbon emissions by 1% increases the cost by an average of 5.46%.
[56]	Belgium	✓	✓		✓			The impact of eight categories of carbon emissions of the battery cycle on climate change	The impacts of direct and reused batteries on climate change are 0.27 and 0.22 $kgCO_2eq/kWh$, respectively.
[57]	Texas, US	✓	✓		✓			Evaluating the effectiveness of SLB on residential communities in a distributed power network	Marginal benefits can be maximized with SLB at low to medium solar penetration.
[58]	Germany, Spain				✓	✓	✓	Analyzing the impact of carbon reduction subsidy of renewable sources on short-term direct program costs	The subsidies for carbon reduction are between 411-1944 €/ton (PV) and 82-276 €/ton (WT).
[59]	China				✓	✓		Evaluation of the effectiveness of the developed subsidy model	The subsidy for CO_2 reduction in regions having high solar energy potential is 0.031-0.044 yuan/kWh.
[60]	Hong Kong, China	✓	✓				✓	Life cycle economic analysis of FB&SLB to provide network resilience services	SLB could be more cost-effective than FB if their initial cost is lower than 214 \$/kWh.

- A carbon tax could save up to 5.2 \$/kg CO_2 reduction cost at lower maximum carbon limits.
- The system cost associated with carbon quotas is reduced by up to 63.6% by increasing the carbon tax.
- NPC would increase up to 122.65% if RF is increased from 95% to 100%.

This paper is organized as follows. Section I presents the literature review and contributions. Section II explains the methodology, mathematical modeling, and assumptions and introduces the HPS model, objective functions, and decision criteria. Section III discusses the scenarios and evaluates the simulation results. Section IV summarizes the discussions. Finally, conclusions and suggestions for future work are given in Section V.

II. MATERIAL AND METHODOLOGY

Section A introduces system modeling. Section B represents the materials. The scenarios are described in Section C. Section D gives the objective function and decision criteria.

A. SYSTEM MODELING

The model design of the hybrid system is presented in Figure 1. The community energy storage in the model represents first and second-use lithium-ion batteries. Prosumers connected to the common busbar use a large-scale common ESS. PV generation is used first for prosumer demand, followed by the common ESS. Excess energy is sold to the grid, while energy is purchased from the grid for higher demand from generation and storage. The energy that cannot be sold to the grid is considered curtailment. The model representing a typical distribution network or small-scale microgrid is included in the cost-based optimization framework, considering only electricity consumption. The first step of the study is the realization of the optimal sizing at the minimum cost objective, followed by evaluating the technical, economic, and environmental feasibility outputs for the scenarios with FB or SLB. ESS throughput and degradation refer only to technical performance, while RF, SCR, SSR and EXR are decision criteria for both technical and environmental performance. NPC and LCOE are considered for economic performance, while environmental concerns are mainly defined by CO_2. In further analysis, the impact of a gradual increase in renewable potential and a carbon tax is also considered, primarily on the extra carbon emission costs and the feasibility results. It can be emphasized that technical issues in the distribution network (power

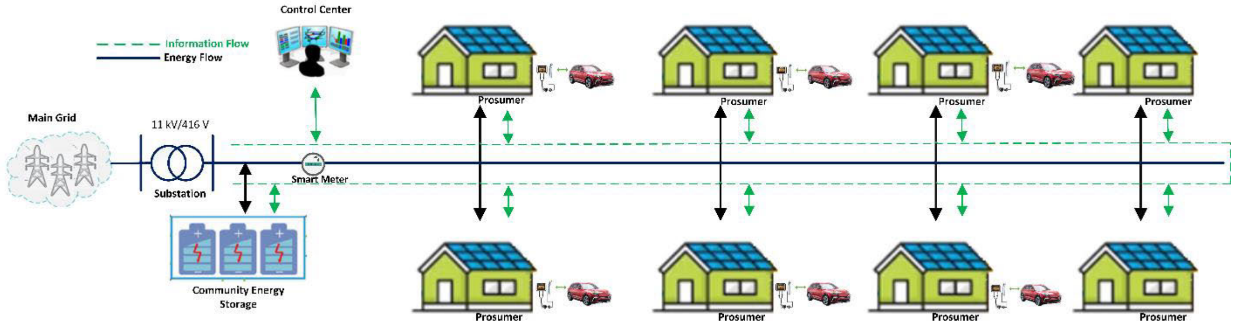


FIGURE 1. System modeling.

loss, voltage drop, harmonics, etc.) are not considered in the study.

PV is widely used in HPS for renewable energy generation. The power generation performance of these panels depends on solar radiation, ambient temperature, tilt angle, and sunshine duration. The power generated by the PV panel at time t is shown in Equation (1) [61], the cell temperature of the PV panel at time t is shown in Equation (2), and the maximum efficiency of the PV panel is shown in Equation (3) [62], [63].

$$P_{PV}(t) = f_{PV}.Y_{PV}.\frac{G_T(t)}{G_{T,STC}}.\left[1+\alpha_P.\left(T_C(t)-T_{C,STC}\right)\right] \tag{1}$$

$$T_C(t) = T_a(t) + \frac{G_T(t)}{G_{T,NOCT}(t)} \cdot \left(T_{Op,NOCT}(t) - T_{Amb,NOCT}(t)\right) \tag{2}$$

$$\eta_{PV} = \frac{Y_{PV}}{A_{PV}.G_{T,STC}} \tag{3}$$

Enabling the improvement of power quality and the efficient and reliable utilization of RES potential, using ESS can provide flexibility for the grid and cost advantages for HPSs. Various ESS models are available; however, electrochemical-type ESSs are frequently used in HPSs. This study utilizes the Lithium-Ion (ASM) model as the ESS in the HOMER PRO software. The aging of the ESS is modeled by four sub-models: functional curve, temperature versus relative capacity curve, DOD-dependent cycle degradation curve, and temperature-dependent shelf-life curve. The instantaneous power dissipation of the ESS is given in Equation (4), and the theoretical capacity value of the ESS is given in Equation (5) [64].

$$P_{out} = I.V_{output} = V_0.I - R_0.I^2 \tag{4}$$

$$I_{Pout,max} = \frac{V_0}{2.R_0} \tag{5}$$

The temperature-dependent capacity can be calculated from Equation (6) using the temperature and battery characteristics shown in Table 2 [64]. Cycle degradation curves for each DOD are available from the ESS manufacturer or can be calculated by Equations (7) and (8) [63]. The loss of capacity can be expressed as a temperature-dependent calendar degradation, irrespective of the use of ESS. The aging by Arrhenius equation is shown by Equation (9) [65], [66].

$$Capacity\,(T) = (Nominal\ Capacity)\,.\left(d_0 + d_1.T + d_2.T^2\right) \tag{6}$$

$$\frac{1}{n} = A.DOD^{\beta} \tag{7}$$

$$D = \sum_{i=0}^{N} A.D_i^{\beta} \tag{8}$$

$$k_t = \frac{1}{Shelf\ life}.\left(capacity\ degradation\ limit\right).e^{-\frac{d}{T}} \tag{9}$$

The maximum charging power and discharging power of the ESS are determined according to the varying SOC, considering three different limitations related to aging at each time step. The first limitation is the kinetic battery model for the maximum charging power, calculated as in Equation (10). The second limitation, the maximum C-rate, is considered in Equation (11), and the third limitation, the maximum ESS charging current, is considered in Equation (12) [64]. The maximum charging power, which aims to minimize the three limitations, is calculated in Equation (13) [63]. The maximum discharge power is determined in Equation (14), while the maximum useful discharge power is calculated in Equation (15) considering the round-trip efficiency [65], [66]. Another consideration is to stop the discharge when the demand power of the ESS exceeds the discharge limit of the storage system's capacity or when the power grid supplies the required load.

$$P_{batt,cmax,kbm} = \frac{k.Q_1.e^{-k.\Delta t} + Q.k.c.\left(1-e^{-k.\Delta t}\right)}{1-e^{-k.\Delta t} + c.\left(k.\Delta t - 1 + e^{-k.\Delta t}\right)} \tag{10}$$

$$P_{batt,cmax,mcr} = \frac{\left(1-e^{-\alpha_c.\Delta t}\right).\left(Q_{max}-Q\right)}{\Delta t} \tag{11}$$

TABLE 2. Technical parameters for FB and SLB packs.

Parameters	FB	SLB
Useful Capacity [kWh]	1	0.8
SOH [%]	100	80
Nominal Voltage [V]	3.7	3.7
Max. Charge Current [A]	270	216
Max. Discharge Current [A]	810	648
Max. Capacity [Ah]	270.27	216
Rate Constant [1/hour]	79.288	161.43
Capacity Ratio	1	1
Effective Series Resistance [mΩ]	0.36049	0.45124
Max. Operating Temperature [°C]	50	50
Min. Operating Temperature [°C]	0	0
Other Round-trip Losses [%]	8	8
Initial SoC [%]	100	100
Min. SoC [%]	20	20
Degradation Limit [%]	50	37.5
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	d_0: 0.923 d_1: 0.00345 d_2:-0.0000375
DOD vs. Cycles to Failure	A: 0.00014423 beta: 1.7945	A: 0.00018029 beta: 1.7945
Shelf-Life vs. Temperature	B: 1.267 d: 3826.70644	B: 1.5838 d: 3826.70644

TABLE 3. System specifications.

Specification	PV (Flat Type)	Converter	FB ESS (Li-Ion ASM)	SLB ESS (Li-Ion ASM)	Grid
Capital cost	1500 $/kW	600 $/kW	550 $/kWh	385 $/kWh	**England TOU:** 0.4750 $/kWh
Replacement cost	1450 $/kW	600 $/kW	500 $/kWh	370 $/kWh	**Spain TOU:** 0.368 $/kWh
O&M cost	10 $/kW/yr	-	10 $/kWh/yr	7 $/kWh/yr	**Türkiye TOU:** 0.12 $/kWh
Degradation limit			50.0%	37.5%	**FIT:** 0.017 $/kWh

$$P_{batt,cmax,mcc} = \frac{N_{batt}.I_{max}.V_{nom}}{1000} \tag{12}$$

$$P_{batt,cmax} = \frac{MIN\left(P_{batt,cmax,kbm}, P_{batt,cmax,mcr}, P_{batt,cmax,mcc}\right)}{\sqrt{\eta_{batt,rt}}} \tag{13}$$

$$P_{batt,dmax,kbm} = \frac{-k.c.Q_{max} + k.Q_1.e^{-k.\Delta t} + Q.k.c.\left(1 - e^{-k.\Delta t}\right)}{1 - e^{-k.\Delta t} + c.\left(k.\Delta t - 1 + e^{-k.\Delta t}\right)} \tag{14}$$

$$P_{batt,dmax} = \sqrt{\eta_{batt,rt}}.P_{batt,dmax,kbm} \tag{15}$$

Since [63] compared SOH and DOD performance for SLB, this study was conducted at 80% SOH and 80% DOD, as shown in Table 2. HPS is equipped with both AC and DC power generation capabilities. DC/AC and AC/DC energy conversions are provided by the power conversion system (PCS). The inverter operating power Equation (16), rectifier operating power Equation (17), and DC/AC inverter ratio Equation (18) can be calculated [67].

$$P_{inv}(t) = \eta_{inv}.P_{DC}(t) \tag{16}$$

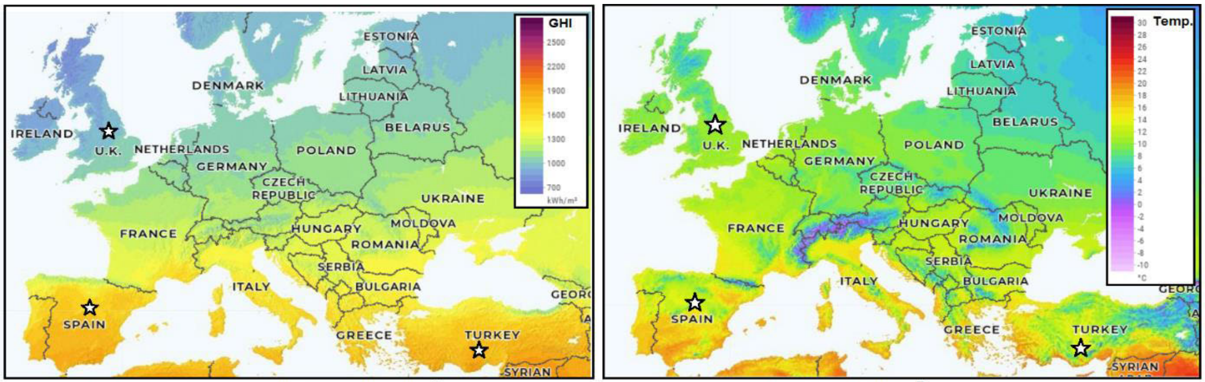
$$P_{rec}(t) = \eta_{rec}.P_{AC}(t) \tag{17}$$

$$\eta_{AC/DC} = \frac{P_{PV}(t)}{P_{PCS}(t)} \tag{18}$$

A load profile has been generated assuming 100 prosumers in the IEEE European LVDN. The daily energy demand of the LVDN is 1427.21 kWh/day. The hourly peak load is 200.83 kW, and the average hourly load is 70.92 kW. The load profile with random variability factors is assumed to be based on the load model average demand for each hour of the day.

B. MATERIALS

Technical and economic system specifications are given in Table 3. The data on global solar horizontal irradiation (GHI) and temperature for European countries are given in



(a) Global Horizontal Irradiation (GHI) (kWh/m^2)

(b) Air Temperature (^{0}C)

FIGURE 2. Solar radiation and temperature data for European countries.

TABLE 4. Meteorological information and economic data of the regions.

Region	England (London)	Spain (Madrid)	Türkiye (Antalya)
Annual average solar GHI	2.72 kWh/m^2/day	4.40 kWh/m^2/day	4.54 kWh/m^2/day
Clearness index	39.54%	54.72%	54.06%
Average temperature	9.38 ^{0}C	14.25 ^{0}C	12.63 ^{0}C

TABLE 5. Scenarios.

Step	Region	Optimal Sizing			CO$_2$ tax ($/t)	Aim
		PV	FB	SLB		
1	England Spain Türkiye	✓	✓	✓	-	Investigate the technical, economic, and environmental impacts of a variation in PV&ESS capacity.
2		✓	-	✓	20	Optimum sizing of the HPS powered by second-life batteries to achieve 100% renewable energy and determination of carbon reduction costs
3		✓	-	✓	0, 20, 40, 60, 80, 100	Assessing additional carbon reduction costs of 100% renewable energy target under different carbon taxes

Figure 2 [68]. Three countries (Spain, England, and Türkiye) were selected to represent the European region as a first step in global planning for a gradual transition to clean energy. The selected countries have different solar radiation and temperature potentials and varying economic conditions such as interest rates, inflation, grid tariffs and electricity selling prices. In addition to the criteria above, population densities were also considered in selecting countries. The average solar radiation and temperatures of each country are given in Table 4.

C. SCENARIOS

Increasing renewable energy potential is just one of the goals of zero-carbon policies. Accordingly, the possible contributions of a prosumer-based distribution grid using shared ESS to clean energy demands must be examined in detail. However, technical grid stability and integrity challenges may arise due to variable and intermittent power generation, especially at high-RES capacities. ESSs can contribute to overcoming these challenges by operating in charge/discharge mode, smoothing the power output of PV plants, and controlling the ramp-rate compliance of the plant. However, countries' economies, power purchase costs, and climatic characteristics can limit the use and benefits of ESS. A different perspective comes from the carbon emissions from increased energy use during the production of FB [15]. Moreover, considering the increasing water use [16] and mineral ore [17], the interest in SLB with lower investment costs will increase. Accordingly, the technical, economic, and environmental advantages and disadvantages of FB and SLB in a shared ESS application were first compared, as shown in Table 5. Based on the proven performance of SLB, the CO$_2$ reduction costs on the path to the 100% renewable energy target are then determined, and possible threshold points in selected countries are assessed. Finally, the potential impact of a carbon tax on CO$_2$ reduction costs at the clean energy target is analyzed at maximum carbon limits.

D. OBJECTIVE FUNCTIONS AND DECISION CRITERIA

The system's total net present cost (NPC) is the value of all revenues generated, less the end-of-life value of all costs. The NPC to be minimized is calculated by summing the total discounted cash flows at the end of the year and dividing the resulting data by the capital recovery factor (CRF). Equation (19) shows the total net present cost, Equation (20) gives the CRF, and Equation (21) represents the annual real discount rate [69].

$$NPC = \frac{C_{ann,tot}}{CRF\,(i,N)} \tag{19}$$

$$CRF\,(i,N) = \frac{i.\,(1+i)^N}{i.\,(1+i)-1} \tag{20}$$

$$i = \frac{i'-f}{1+f} \tag{21}$$

The total annual cost is the sum of the costs associated with HPS at the end of the first year. In addition, annual cost items such as capital cost, replacement cost, operation, and maintenance (O&M) cost, fuel cost, grid purchases, and carbon tax are also considered in the NPC. Equations (22), (23), and (24) show the total annual cost, investment, and maintenance costs. The carbon tax is determined by Equation (25), the electricity purchase is calculated by Equation (26), and the revenue from electricity sales is computed by Equation (27) [61].

$$C_{ann,tot} = C_{inv} + C_{main} + C_{tax} + C_{GP} - C_{GS} \tag{22}$$

$$C_{inv} = CRF\,(i,n)\,.\sum_{\ell=0}^{\ell_0} IC\,(\ell)\,.C_{cap}\,(\ell) \tag{23}$$

$$C_{main} = \varepsilon.\sum_{\ell=0}^{\ell_0} IC\,(\ell)\,.C_{cap}\,(\ell) \tag{24}$$

$$C_{tax} = CO_{tax}.\lambda.\sum_{t=1}^{8760} E_{GP}\,(t) = CO_{tax}.TCO_2 \tag{25}$$

$$C_{GP} = \sum_{t=1}^{8760} E_{GP}\,(t)\,.C_{buy}\,(t) \tag{26}$$

$$C_{GS} = \sum_{t=1}^{8760} E_{GS}\,(t)\,.C_{sell}\,(t) \tag{27}$$

The average energy cost produced is the LCOE defined in Equation (28) [70]. Besides NPC, low LCOEs represent a secondary objective.

$$LCOE = \frac{C_{ann,tot}}{E_{served}} = \frac{C_{ann,tot}}{E_{load} + E_{EV}} \tag{28}$$

Environmental performance is assessed by multiplying the possible electricity purchased from the grid at each hour of the year by the CO_2 per unit of energy in the grid mix and cumulatively summing in Equation (29) [71]. On the road to 100% renewable energy, CO_2 minimization is as critical a study objective as cost reduction.

$$TCO_2 = \lambda.\sum_{t=1}^{8760} E_{GP}\,(t) \tag{29}$$

The RF indicates the ratio of the total annual energy obtained from the RES to be transferred to the load, as given in Equation (30) [72].

$$RF = 1 - \frac{E_{nonren}}{E_{served}} \tag{30}$$

Self-consumption ratio (SCR) is the ratio of renewable energy transferred directly to the load to the total renewable energy, as represented in Equation (31) [73].

$$SCR = \frac{E_{RES}^{cons}}{E_{RES}} \tag{31}$$

Self-supply ratio (SSR) is the ratio of renewable energy transferred directly to the load to the total load, as shown in Equation (32) [73].

$$SSR = \frac{E_{RES}^{cons}}{E_{served}} \tag{32}$$

III. SIMULATION RESULTS

The technical, economic, and environmental impacts of the increase in prosumer PV&FB ESS installed capacity are presented in Figure 3. In countries with high solar radiation potential, such as Türkiye and Spain, SCRs vary depending on PV capacity between 34.7-86.5% in non-FB scenarios. According to the PV generation and load overlap, SCRs are similarly maximized at installed capacities below 300 kW. In contrast, above this value, SCRs vary up to 22% depending on the solar potential of the countries. For example, at the installed capacity of 500 kW in England, the SCR increases to 71.3% in optimal scenarios. In contrast, this value can grow to a maximum of 55.8% for the same scenario in Türkiye. However, the SSR is up to 28% lower in England. In addition, PV capacity expansion can decrease grid dependency by up to 46% in non-FB scenarios, while FB utilization can increase it by up to 2 times. Energy purchase costs are lower in Türkiye, where FB has raised discounted payback period (DP), and project amortization processes have not been realized. Depending on solar radiation in England, the EXR for a 500 kW PV installed capacity was up to 35% longer than in the other two countries. In Spain, where energy purchase costs are high, consumers have avoided the grid and used FB. Utilizing FB in England is economical for PV installed capacities above 100 kW; in these scenarios, the DP can be reduced by up to 7 years. Although the use of FB in Spain is favorable for PV installed capacities above 200 kW, the DP is reduced by up to 5 years in optimal scenarios. On the other hand, in Türkiye, the optimum economic results are realized in scenarios without FB, and DP is reduced by up to 12 years. ESSs can facilitate enabling an energy system that increases the energy independence of the community by reducing the net energy exchange.

Optimistic climate zones with high solar potential can increase RF by up to 86.6% with the adoption of ESSs. However, poor choices of decision-makers can make the sizing misleading. This can be exemplified by the increase

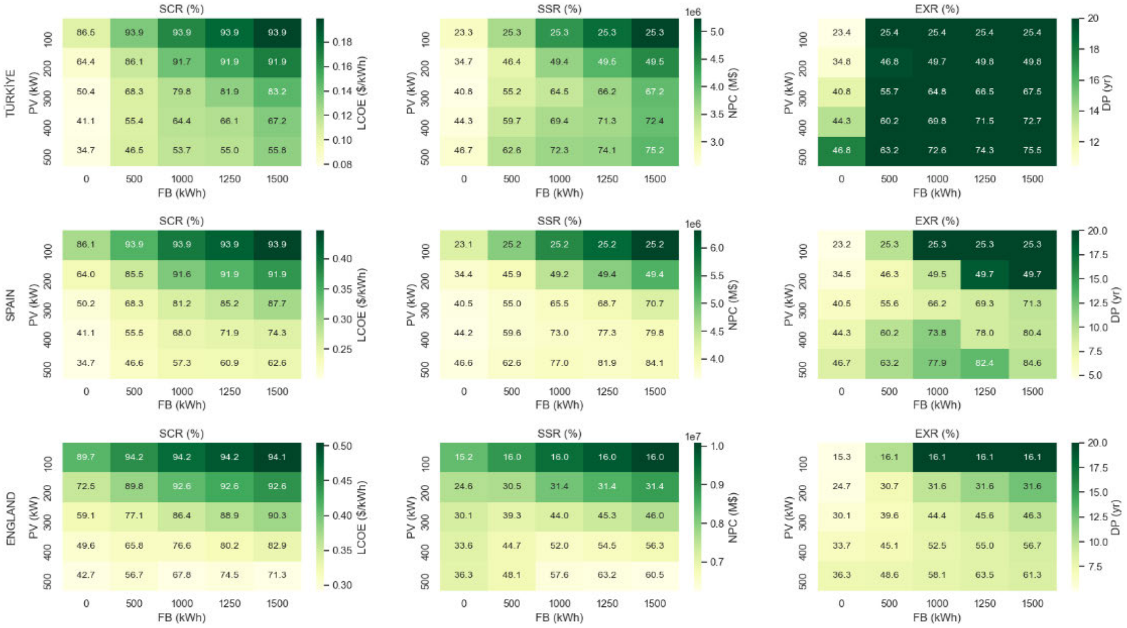


FIGURE 3. Analyzing the technical, economic, and environmental impacts of PV&FB ESS capacity change.

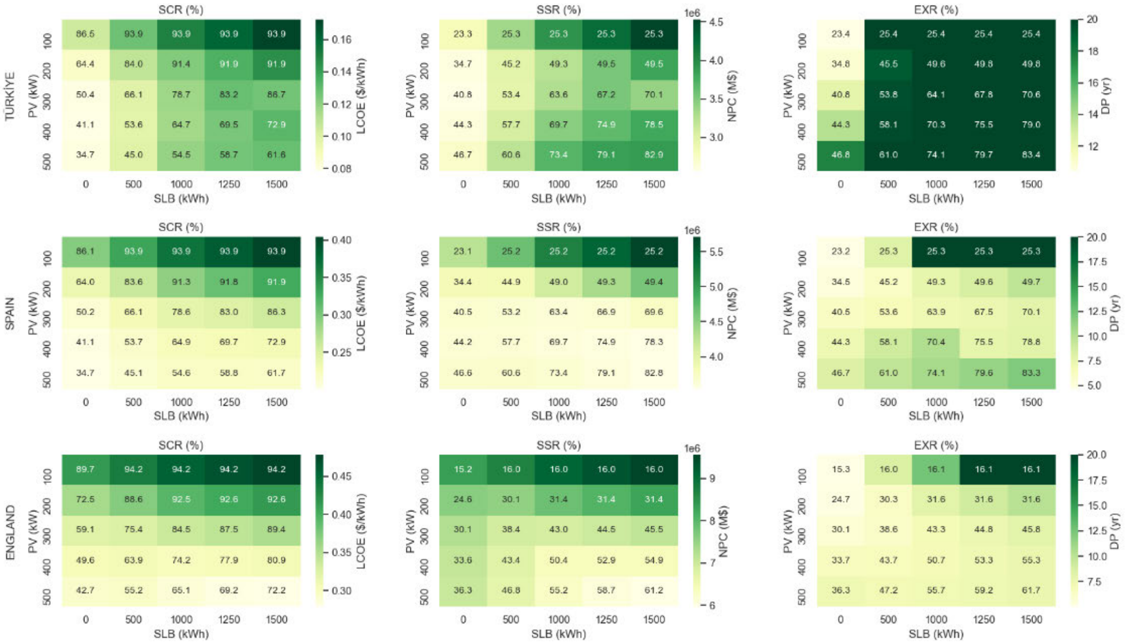


FIGURE 4. Analyzing the technical, economic, and environmental impacts of PV&SLB ESS capacity change.

of CE up to 21.16% in FB and 18% in SLB scenarios. Therefore, it has always been essential to harmonize PV and ESS capacity. On the other hand, regardless of the battery option, Spain and Türkiye are one step closer to harmonization with a 40% reduction in PV capacity compared to the optimal scenarios. At the same time, in England, it is 20%. Regarding the capacity choice, FB&SLB can minimize CE while the SCR increases to 25.12% and 16.84%, respectively. However, increasing LCOE and decreasing SSR, battery utilization, and average DOD reduce the attractiveness. On the other hand, less utilization of ESS due to its cost reduces battery degradation by up to 9%, recovering the cost-benefit relationship to some extent. Besides the reduced and insufficient PV capacity, reducing the BESS capacity increases the grid dependency and reduces the economic demand reliability. Reducing the FB capacity to 50% in each climate

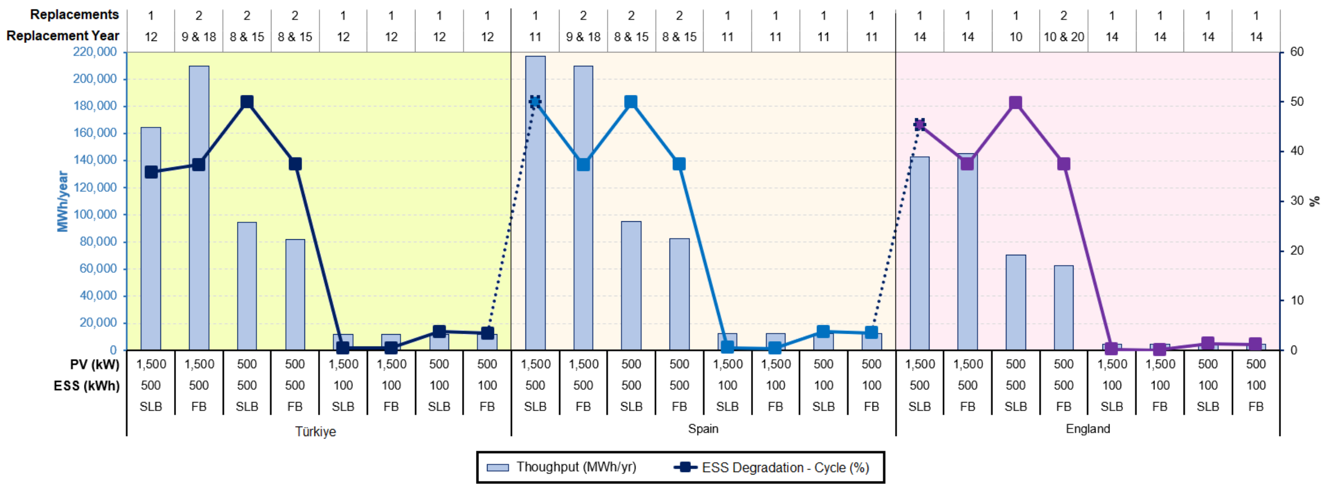


FIGURE 5. The performance of FB&SLB in different climates.

zone increased the CE by 3.25%, but the return on investment (ROI) and annual battery utilization could be improved by 2.8% and 37.62%. However, $\text{DOD}_{\text{average}}$ increased to 44.21%, but degradation increased by 15.06%, reducing SCR by 12.09% and lowering the benefit. On the other hand, increasing $\text{DOD}_{\text{average}}$ and SSR by 4.64% and 6.3% throughout the year and reducing degradation by 11.52% makes SLB superior. Due to the dominance of benefits, DP can be shortened by 2.02 years. As a result, storage superiority may vary depending on the decision criteria. For instance, FB-based HPS can increase SSR to 12.51% and prevent ESS degradation by up to 6.25% in Türkiye. However, Spain can increase $\text{DOD}_{\text{average}}$ by 9.41%, battery utilization by up to 33.33%, and reduce the equivalent cycle by 18%. Besides optimistic battery aging performance, CO_2 can be reduced by 33.6%. Therefore, the feasibility of storage with FB based on battery technology and clean energy criteria changes in favor of Spain.

The performance of SLB in different climate regions can be seen in Figure 4. SLB-based HPS can reduce LCOE by up to 59.1% and address environmental concerns by up to 34.16%. Increasing renewable energy potential can reduce EXR by 15.3% and SCR by 3%. In addition, the battery's efficiency can be increased by 37.6 % and thus the equivalent cycle by 20.4 %. Thus, the $\text{DOD}_{\text{average}}$ over the year can be increased by up to 10.63%. Thanks to their efficient economy, SLB can reduce LCOE by 14.3% and CO_2 by 9.4% compared to FB. Moreover, it maximizes the benefit of FB by increasing battery throughput by 11.5%, $\text{DOD}_{\text{average}}$ by 11%, and equivalent cycle by up to 14.8% in the supply-demand balance. However, usage-dependent battery degradation may increase by 6.22%. Finally, the dominance of benefits can shorten the simple payback period (SP) by 2.21 years, while the internal rate of return (IRR) can be increased up to 4%.

To extend the comparison between FB and SLB in ESS applications, the technical performance of battery replacement years and the number of battery replacements, throughput, and cycle degradation are examined in Figure 5.

PV capacity up to 300 kW increases FB cycle degradation up to 5.3% in high renewable potential Spain. On the other hand, degradation is 11.3% higher in Türkiye, which has a better solar energy potential than in England. However, the FB efficiencies of prosumers avoiding electricity tariffs and shifting to clean energy are 31% higher with increasing PV capacity. Countries with low electricity tariffs, such as Türkiye, are less likely to utilize batteries with high initial costs. Similar situations are also observed in SLB. However, these batteries, which have experienced degradation in the first use, have a 3.1-7% slower degradation tendency for second use despite the increasing PV capacity. On the other hand, 20% less capacity does not mean the throughput in the supply-demand balance will be lower. In contrast, due to the lower investment cost, its utilization has increased to 15.6% compared to FB. Differently, independently of the first or second use of the batteries, with the PV capacity rising to 300 kW, the batteries were replaced only once during the project's lifetime. In addition, the battery replacement occurred three years ago, owing to the higher rate of battery degradation in Spain. Battery replacement occurs later in England (14th year) due to reduced degradation rates. Although a similar trend is realized with the increase of PV capacity to 500 kW, the degradation and throughput changes are less. Also, SLB replacement (2 times) could not be avoided in Spain and Türkiye. Moreover, the second replacement period in Spain occurred one year ago. The increase in the capacity of ESS affects professional consumers with PV capacity installations of more than 300 kW. Increasing battery capacities in these scenarios effectively improves ESS throughput and reduces grid dependency. Moreover, as DOD is reduced depending on demand, cycle degradation is reduced. Accordingly, SLB throughput is 42.5% higher than FB in England, which is seeking lower-cost energy

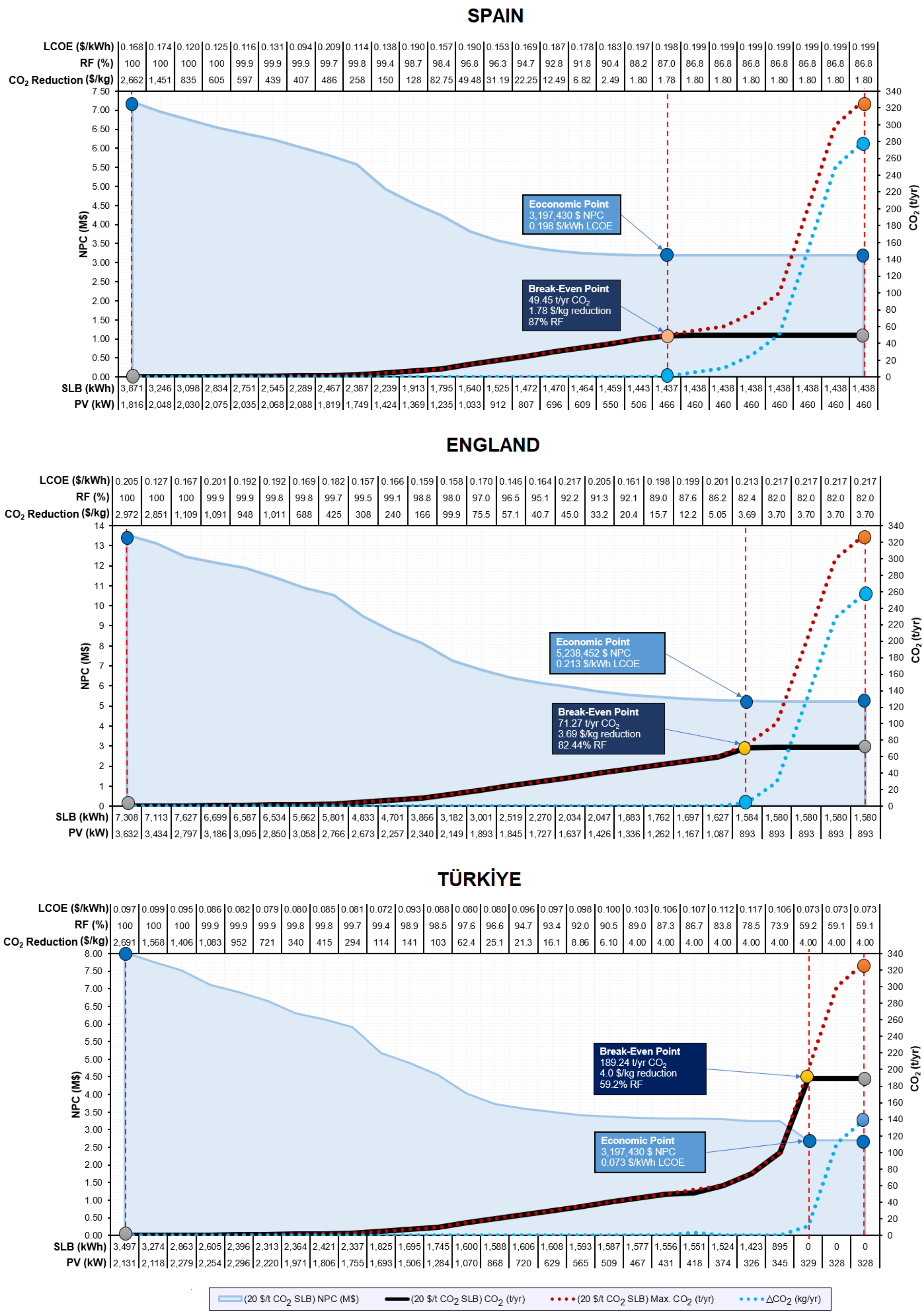


FIGURE 6. Optimal sizing break-even points of different regions depending on the renewable fraction.

alternatives. In other climatic regions, the throughput benefit is reduced to 37.5%. However, with increasing ESS capacity, a high increase in SLB utilization compared to FB can increase cycle degradation by 15%, especially in England. The combined rise of PV&ESS capacity can increase the RF to 86.6%. However, the increase of CE to 21.6% causes HPS sizing inefficiency. Moreover, the battery replacement period increases, prolonging the payback period of the investment.

The CO_2 reduction cost of a gradual increase in RF at a 100% renewable target can be seen in Figure 6. In addition, by evaluating the increase in NPC relative to the minimum cost optimal HPS sizes, break-even points on the path to clean energy were determined for three different regions.

In countries like Türkiye, where electricity tariffs are relatively low, grid dependency is high. Therefore, there is an early break-even point at the upper levels of CO_2 reduction limits, i.e., 200 t/y, and economic outcomes can be at risk at RF values of 59.2% and above. However, Spain's relatively better economic parameters and weather conditions led to a break-even point at 50 t/y with an RF of 87%. In England, where electricity tariffs are high, weather conditions are poor, the break-even point reached 75 t/y with a corresponding RF of 82.44%. On the other hand, although not shown in the figure, similar break-even points were observed for FB. The NPC at the break-even point with FB preference is 5.5%, 3.4%, and 11.06% higher in Spain, England, and Türkiye, respectively. However, carbon emissions are 1.17%, 0.47%, and 17.5% lower in Spain, England, and Türkiye, respectively.

Table 6 summarizes the possible changes in HPS capacities, CO_2 reduction cost, NPC, CE, LCOE, and CO_2 for possible RF transitions towards the 100% renewable energy target. For RF transitions from 85% to 90%, the CO_2 reduction cost is up to 10 \$/kg higher in England, and the technical, economic, and environmental changes are more significant. While the situation for rising RF transitions is the same regarding CO_2 reduction cost, the changes in feasibility outcomes are more significant in Türkiye. While reductions in LCOE and CO_2 are critical in moving towards the clean energy target, it is clear from the increases in NPC that prosumers need to be supported by governments.

CO_2 must be maximally limited to increase the RF; therefore, the additional financial obligation to reduce CO_2 cannot be avoided. At lower carbon reduction levels, the cost of carbon reduction in Türkiye, with its high grid dependency, can reach 16 \$/kg. In contrast, there are extra financial obligations of 12.5 \$/kg in England and 4.5 \$/kg in Spain. FB can increase additional costs by up to 2.1 \$/kg at low reduction levels compared to SLB. On the other hand, in England, with high energy prices, extra costs could increase to 1445.5 \$/kg for SLB and 1302 \$/kg for FB at high reduction targets. While SLB does not seem to support extra financial increases compared to FB for low carbon reduction targets, the opposite is the case in England and Türkiye regarding higher carbon reduction targets, which can cause extra costs of up to 352.3 \$/kg. On the contrary, the SLB retains its advantage in Spain and can reduce costs by up to 100.3 \$/kg. In Figure 7, CO_2 reduction costs, determined according to maximum carbon limits, are evaluated in a progressive carbon tax. Providing flexibility in carbon reduction makes the impact of progressive carbon taxes on the cost of CO_2 reduction more significant. A progressive carbon tax could reduce CO_2 reduction costs by up to 4.1 \$/kg in England, 2.1 \$/kg in Spain, and 5.2 \$/kg in Türkiye. Higher financial savings are inherent in Türkiye with its high grid dependency. The system cost associated with carbon quotas is reduced by 31.5%, 46%, and 63.6% for England, Türkiye, and Spain by increasing the carbon tax. As a result of the stricter carbon reduction, the impacts of a carbon tax are not high due to reduced grid dependency and increased renewable capacity due to the limitations. In contrast to England and Spain, where energy prices are relatively higher, potential increases in the carbon tax are more effective in Türkiye. After all, increased CO_2 taxes can reduce the financial obligations of prosumers with increased RES installations in countries. Implementing the CO_2 reduction target is relatively more difficult in Türkiye, where electricity prices are lower. In contrast, CO_2 reduction targets are easier to achieve in Spain. Countries with high electricity tariffs, such as England, can be advantageous in the middle stages of the clean energy transition.

IV. DISCUSSION

The results illustrate several important considerations and challenges for achieving zero-carbon goals. The work in [74] is consistent with this study in that the cost increases non-linearly to achieve higher RF, especially as RF approaches 100%. For instance, increasing the RF from 95% to 100% increased the NPC up to 122.65% due to the additional PV and ESS capacities of around 200%. However, less use of larger ESS reduces battery degradation by up to 9% and slightly improves the cost-benefit ratio. A similar study emphasized that the nominal ESS capacity for 100% renewable energy in Western NY is 83,011 MWh, most of which is never used but is held in reserve for a few peak hours on hot summer days. This study also highlighted that increasing the battery capacity to increase the RF from 95% to 100% increases the system cost by approximately 300% [75].

An essential aspect of SLB is reducing the LCOE by up to 14.3% towards increasing the use of clean energy to eliminate grid dependency. Compared to FB in similar studies, SLB reduces the levelized cost of electricity (LCOE) by 12-41% [33] and 35% [31]. Conversely, increasing FB capacity reduces grid dependency up to 2 times more than the scenarios with SLB. However, the analysis results indicate that the choice of FB increases the NPC by 3.4% to 11.06%. Another important parameter that affects battery utilization is the cost of grid energy purchase. In Spain, where energy purchase costs are high, prosumers avoid the grid and prefer FB, while in optimal scenarios, DP decreases for up to 5 years. In Türkiye, optimal results are obtained in scenarios without FB due to low energy purchase costs. Therefore, it is even more important to consider the energy purchase costs

TABLE 6. Possible changes in prosumer feasibility towards 100% renewable energy target.

Regions	RF change from ...% to ...%	Extra cost	Increase (%)				Decrease (%)	
		CO_2 Reduction ($/kg)	PV Capacity	SLB Capacity	NPC	CE	LCOE	CO_2
Spain	85 => 90	0.69	19.56	1.46	0.66	4.3	8.04	20
	90 => 95	19.76	46.73	0.89	6.33	14.89	7.65	36.96
	95 => 100	2639.75	125.03	162.97	111.25	2.27	0	100
England	85 => 90	10.65	16.1	8.3	2.66	5.1	1.52	16.79
	90 => 95	25	36.85	28.83	12.8	1.7 (-)	17.17	40
	95 => 100	2931.3	110.3	221.94	120.88	8.71	25 (+)	100
Türkiye	85 => 90	2.1	21.77	2.32	1.79	6	6.54	22.66
	90 => 95	15.2	41.45	1.2	6.81	15.77	4	37.55
	95 => 100	2669.7	195.97	117.75	122.65	17.02	0	100
Annotate:	Carbon tax :20 $/ton (-) : Indicates a decrease when it should increase. (+) : Indicates that it increased when it should have decreased.							

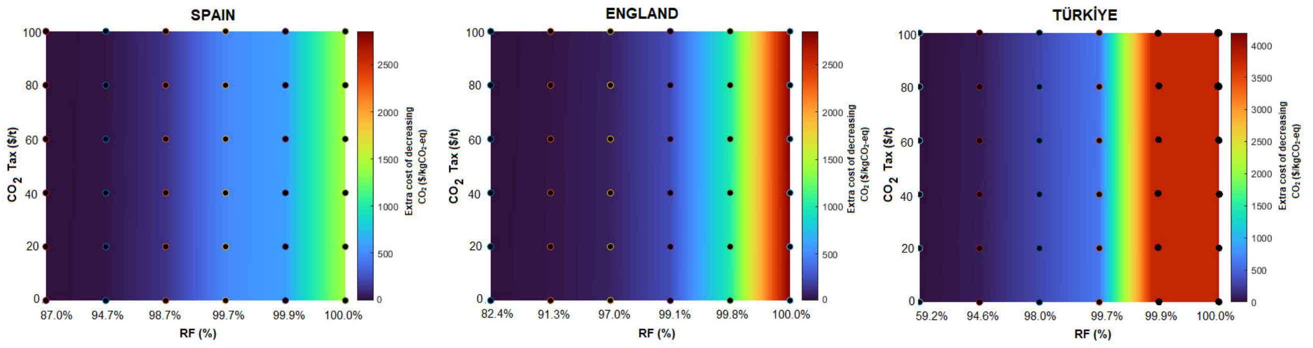


FIGURE 7. Assessment of additional carbon reduction costs of a 100% renewable energy target considering levelized carbon tax.

in the context of clean energy targets when planning storage subsidies [36]. The optimal RF depends on the local availability of renewable resources and other economic parameters such as energy purchase costs, inflation, and interest rates. In regions with high solar radiation potential, the RF can be increased up to 86.6% with the implementation of ESS if the economic parameters are also favorable. The RF cannot be increased by more than 59% in countries with lower electricity tariffs, such as Türkiye, because even SLB is expensive. In contrast, in countries with high electricity tariffs, such as Spain, RF can be increased by 28% more thanks to ESS.

Increasing carbon tax does not positively affect the RES penetration [34]. Investors may prefer wind power to coal-fired power plants when the carbon tax reaches 30 yuan/ton [51]. In contrast, it is suggested that if the cost of carbon penalty in Korea can be kept below 83 $/ton CO_2-eq, it will favor domestic RES production [49]. In addition, a possible decrease in electricity purchase prices reduces the benefit of the carbon tax [45]. At low carbon limits, carbon reduction costs are 16 $/kg in high grid-dependency Türkiye and 4.5 $/kg in low grid-dependency Spain. Therefore, since electricity prices are lower in Türkiye, it is relatively more challenging to achieve the CO_2 reduction target. SLB can reduce carbon reduction costs by an additional 2.1 $/kg compared to FB when the carbon limit is lowered. However, at higher carbon limits, using SLB could result in additional costs of up to 352.3 $/kg in England and Türkiye. In contrast, the SLB retains its advantage in Spain, where it reduces the carbon reduction costs by up to 100.3 $/kg. Similar studies also show that increasing carbon tax impacts the cost of carbon reduction [46], [47], [48]. The results show that prosumers must gradually be subsidized towards 100% renewable energy targets. Notably, integrating SLB-RES instead of FB provides a sustainable energy supply with a reliable supply-demand balance.

V. CONCLUSION

This study comparatively evaluates the optimal HPS with minimum cost for prosumers using FB or SLB as shared energy storage in different climate regions in technical, economic, and environmental perspectives. The impacts of the optimal PV and ESS size on the feasibility outputs in the scenarios with FB or SLB are analyzed. The feasibility of HPS is evaluated considering the gradual increase in RF for carbon limits and tax on the path to 100% renewable energy. Moreover, the possible effects of a carbon tax on CO_2 reduction costs based on maximum carbon limits are analyzed. Possible carbon taxes for prosumers, who should be rewarded for the extra financial obligations caused by the reduction of carbon emissions in carbon neutrality goals, are evaluated and how financial welfare can be improved is detailed. However, since the focus is on cost-based optimal sizing and feasibility analysis, the study does not consider technical aspects on the distribution grid side (power loss, voltage drop, power factor, harmonics, etc.). Additionally, analyses were carried out for three countries, considering climatic characteristics, economic conditions, and population densities. The results proved the SLB-based HPS's benefits in addressing the climate crisis. SLB can reduce LCOE by 14.3% and increase self-consumption potential by up to 2%, even though storage superiority varies depending on the decision criteria. Furthermore, increasing the battery throughput by 11.5% and equivalent cycle up to 14.8% maximizes the benefit to FB. RFs above 87%, 82.44% and 59.2% lead to costly HPS investments in Spain, the England and Türkiye, respectively. Severely limiting the carbon limit for the 100% renewable target would increase the cost of carbon reduction by up to 2851.3 \$/kg and lead to costly investments. An increase in the carbon tax could save up to 5.2 \$/kg in CO_2 reduction costs at lower CO_2 limits, but at higher CO_2 limits, the carbon tax has little impact on extra costs. Increasing the RF from 95% to 100% increases the NPC up to 122.65% due to approximately 200% additional PV and ESS capacity. According to the results, the financial obligations of prosumers should be subsidized according to categorized carbon limits or RF targets. The findings of this study can be extended using clean energy policies such as gradual feed-in tariff reduction, net metering, net billing, and investment discounts. Future research can investigate the feasibility of energy investments and targets in different climatic and economic regions on a global scale, considering power quality constraints in distribution networks and the gradual transition to clean energy.

REFERENCES

[1] D. S. Pisetsky, "The breakthrough," *Ann. Internal Med.*, vol. 124, no. 3, p. 345, Feb. 1996, doi: 10.7326/0003-4819-124-3-199602010-00013.

[2] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation," *Energy Strategy Rev.*, vol. 24, pp. 38–50, Apr. 2019, doi: 10.1016/j.esr.2019.01.006.

[3] *World Energy Transitions Outlook*, International Renewable Energy Agency (IRENA), Masdar City, United Arab Emirates, 2022.

[4] IRENA, "Renewable energy targets in 2022: A guide to design," Abu Dhabi, 2022.

[5] *Net Zero by 2050: A Roadmap for the Global Energy Sector*, IEA, International Energy Agency, Paris, France, 2021, p. 224.

[6] S. Sambhi, H. Sharma, V. Bhadoria, P. Kumar, R. Chaurasia, G. Fotis, and V. Vita, "Technical and economic analysis of solar PV/Diesel generator smart hybrid power plant using different battery storage technologies for SRM IST, delhi-NCR campus," *Sustainability*, vol. 15, no. 4, p. 3666, Feb. 2023, doi: 10.3390/su15043666.

[7] R. Z. Falama, M. D. Kaoutoing, F. K. Mbakop, V. Dumbrava, S. Makloufi, N. Djongyang, C. B. Salah, and S. Y. Doka, "A comparative study based on a techno-environmental-economic analysis of some hybrid grid-connected systems operating under electricity blackouts: A case study in Cameroon," *Energy Convers. Manage.*, vol. 251, Jan. 2022, Art. no. 114935, doi: 10.1016/j.enconman.2021.114935.

[8] X. Qi, J. Wang, G. Królczyk, P. Gardoni, and Z. Li, "Sustainability analysis of a hybrid renewable power system with battery storage for islands application," *J. Energy Storage*, vol. 50, Jun. 2022, Art. no. 104682, doi: 10.1016/j.est.2022.104682.

[9] H. He, E. Du, N. Zhang, C. Kang, and X. Wang, "Enhancing the power grid flexibility with battery energy storage transportation and transmission switching," *Appl. Energy*, vol. 290, May 2021, Art. no. 116692, doi: 10.1016/j.apenergy.2021.116692.

[10] G. Yanagawa and H. Aki, "Grid flexibility provision by optimization of fast-charging demand of battery electric vehicles," *IEEE Trans. Smart Grid*, vol. 14, no. 3, pp. 2202–2213, May 2023, doi: 10.1109/TSG.2022.3219403.

[11] H. Ren, Z. Ma, A. M. L. Fong, and Y. Sun, "Optimal deployment of distributed rooftop photovoltaic systems and batteries for achieving net-zero energy of electric bus transportation in high-density cities," *Appl. Energy*, vol. 319, Aug. 2022, Art. no. 119274, doi: 10.1016/j.apenergy.2022.119274.

[12] X. Han, J. Garrison, and G. Hug, "Techno-economic analysis of PV-battery systems in Switzerland," *Renew. Sustain. Energy Rev.*, vol. 158, Apr. 2022, Art. no. 112028, doi: 10.1016/j.rser.2021.112028.

[13] H. Jacobus, B. Lin, D. H. Jimmy, R. Ansumana, A. P. Malanoski, and D. Stenger, "Evaluating the impact of adding energy storage on the performance of a hybrid power system," *Energy Convers. Manage.*, vol. 52, no. 7, pp. 2604–2610, Jul. 2011, doi: 10.1016/j.enconman.2011.01.015.

[14] J. Liu, M. Wang, J. Peng, X. Chen, S. Cao, and H. Yang, "Techno-economic design optimization of hybrid renewable energy applications for high-rise residential buildings," *Energy Convers. Manage.*, vol. 213, Jun. 2020, Art. no. 112868, doi: 10.1016/j.enconman.2020.112868.

[15] S. D. Kurland, "Energy use for GWh-scale lithium-ion battery production," *Environ. Res. Commun.*, vol. 2, no. 1, Jan. 2020, Art. no. 012001, doi: 10.1088/2515-7620/ab5e1e.

[16] K. Amit, "The spiralling environmental cost of our lithium battery addiction," *Wired UK*, vol. 9, pp. 1–15, Aug. 2018.

[17] P. Meshram, B. D. Pandey, and T. R. Mankhand, "Extraction of lithium from primary and secondary sources by pre-treatment, leaching and separation: A comprehensive review," *Hydrometallurgy*, vol. 150, pp. 192–208, Dec. 2014, doi: 10.1016/j.hydromet.2014.10.012.

[18] M. H. S. M. Haram, J. W. Lee, G. Ramasamy, E. E. Ngu, S. P. Thiagarajah, and Y. H. Lee, "Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges," *Alexandria Eng. J.*, vol. 60, no. 5, pp. 4517–4536, Oct. 2021, doi: 10.1016/j.aej.2021.03.021.

[19] C. A. Rufino Jr., E. R. Sanseverino, P. Gallo, D. Koch, H.-G. Schweiger, and H. Zanin, "Blockchain review for battery supply chain monitoring and battery trading," *Renew. Sustain. Energy Rev.*, vol. 157, Apr. 2022, Art. no. 112078, doi: 10.1016/j.rser.2022.112078.

[20] E. Martinez-Laserna, I. Gandiaga, E. Sarasketa-Zabala, J. Badeda, D.-I. Stroe, M. Swierczynski, and A. Goikoetxea, "Battery second life: Hype, hope or reality? A critical review of the state of the art," *Renew. Sustain. Energy Rev.*, vol. 93, pp. 701–718, Oct. 2018, doi: 10.1016/j.rser.2018.04.035.

[21] M. Shahjalal, P. K. Roy, T. Shams, A. Fly, J. I. Chowdhury, M. R. Ahmed, and K. Liu, "A review on second-life of Li-ion batteries: Prospects, challenges, and issues," *Energy*, vol. 241, Feb. 2022, Art. no. 122881, doi: 10.1016/j.energy.2021.122881.

[22] Y. Tao, C. D. Rahn, L. A. Archer, and F. You, "Second life and recycling: Energy and environmental sustainability perspectives for high-performance lithium-ion batteries," *Sci. Adv.*, vol. 7, no. 45, pp. 1–17, Nov. 2021, doi: 10.1126/sciadv.abi7633.

[23] C. Ioakimidis, A. Murillo-Marrodán, A. Bagheri, D. Thomas, and K. Genikomsakis, "Life cycle assessment of a lithium iron phosphate (LFP) electric vehicle battery in second life application scenarios," *Sustainability*, vol. 11, no. 9, p. 2527, May 2019, doi: 10.3390/su11092527.

[24] L. Colarullo and J. Thakur, "Second-life EV batteries for stationary storage applications in local energy communities," *Renew. Sustain. Energy Rev.*, vol. 169, Nov. 2022, Art. no. 112913, doi: 10.1016/j.rser.2022.112913.

[25] J. Thakur, C. M. L. de Almeida, and A. G. Baskar, "Electric vehicle batteries for a circular economy: Second life batteries as residential stationary storage," *J. Cleaner Prod.*, vol. 375, Nov. 2022, Art. no. 134066, doi: 10.1016/j.jclepro.2022.134066.

[26] J. Lacap, J. W. Park, and L. Beslow, "Development and demonstration of microgrid system utilizing second-life electric vehicle batteries," *J. Energy Storage*, vol. 41, Sep. 2021, Art. no. 102837, doi: 10.1016/j.est.2021.102837.

[27] L. Canals Casals, M. Barbero, and C. Corchero, "Reused second life batteries for aggregated demand response services," *J. Cleaner Prod.*, vol. 212, pp. 99–108, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.005.

[28] L. C. Casals, B. Amante García, and C. Canal, "Second life batteries lifespan: Rest of useful life and environmental analysis," *J. Environ. Manage.*, vol. 232, pp. 354–363, Feb. 2019, doi: 10.1016/j.jenvman.2018.11.046.

[29] J. Li, S. He, Q. Yang, T. Ma, and Z. Wei, "Optimal design of the EV charging station with retired battery systems against charging demand uncertainty," *IEEE Trans. Ind. Informat.*, vol. 19, no. 3, pp. 3262–3273, Mar. 2023, doi: 10.1109/TII.2022.3175718.

[30] T. Steckel, A. Kendall, and H. Ambrose, "Applying levelized cost of storage methodology to utility-scale second-life lithium-ion battery energy storage systems," *Appl. Energy*, vol. 300, Oct. 2021, Art. no. 117309, doi: 10.1016/j.apenergy.2021.117309.

[31] A. Bhatt, W. Ongsakul, and M. N. Madhu, "Optimal techno-economic feasibility study of net-zero carbon emission microgrid integrating second-life battery energy storage system," *Energy Convers. Manage.*, vol. 266, Aug. 2022, Art. no. 115825, doi: 10.1016/j.enconman.2022.115825.

[32] N. Horesh, C. Quinn, H. Wang, R. Zane, M. Ferry, S. Tong, and J. C. Quinn, "Driving to the future of energy storage: Techno-economic analysis of a novel method to recondition second life electric vehicle batteries," *Appl. Energy*, vol. 295, Aug. 2021, Art. no. 117007, doi: 10.1016/j.apenergy.2021.117007.

[33] D. Kamath, R. Arsenault, H. C. Kim, and A. Anctil, "Economic and environmental feasibility of second-life lithium-ion batteries as fast-charging energy storage," *Environ. Sci. Technol.*, vol. 54, no. 11, pp. 6878–6887, Jun. 2020, doi: 10.1021/acs.est.9b05883.

[34] D. Kamath, S. Shukla, R. Arsenault, H. C. Kim, and A. Anctil, "Evaluating the cost and carbon footprint of second-life electric vehicle batteries in residential and utility-level applications," *Waste Manage.*, vol. 113, pp. 497–507, Jul. 2020, doi: 10.1016/j.wasman.2020.05.034.

[35] E. Dogan, S. Hodžić, and T. F. Šikić, "Do energy and environmental taxes stimulate or inhibit renewable energy deployment in the European Union?" *Renew. Energy*, vol. 202, pp. 1138–1145, Jan. 2023, doi: 10.1016/j.renene.2022.11.107.

[36] F. G. Üçtuğ and A. Azapagic, "Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries," *Sci. Total Environ.*, vol. 643, pp. 1579–1589, Dec. 2018, doi: 10.1016/j.scitotenv.2018.06.290.

[37] Y. A. Solangi, C. Longsheng, and S. A. A. Shah, "Assessing and overcoming the renewable energy barriers for sustainable development in Pakistan: An integrated AHP and fuzzy TOPSIS approach," *Renew. Energy*, vol. 173, pp. 209–222, Aug. 2021, doi: 10.1016/j.renene.2021.03.141.

[38] Á. Ordóñez, E. Sánchez, L. Rozas, R. García, and J. Parra-Domínguez, "Net-metering and net-billing in photovoltaic self-consumption: The cases of Ecuador and Spain," *Sustain. Energy Technol. Assessments*, vol. 53, Oct. 2022, Art. no. 102434, doi: 10.1016/j.seta.2022.102434.

[39] X. Luo, Y. Liu, and X. Liu, "Bi-level multi-objective optimization of design and subsidies for standalone hybrid renewable energy systems: A novel approach based on artificial neural network," *J. Building Eng.*, vol. 41, Sep. 2021, Art. no. 102744, doi: 10.1016/j.jobe.2021.102744.

[40] L. Gao, Y. Hiruta, and S. Ashina, "Promoting renewable energy through willingness to pay for transition to a low carbon society in Japan," *Renew. Energy*, vol. 162, pp. 818–830, Dec. 2020, doi: 10.1016/j.renene.2020.08.049.

[41] M. Herrando, A. Ramos, and I. Zabalza, "Cost competitiveness of a novel PVT-based solar combined heating and power system: Influence of economic parameters and financial incentives," *Energy Convers. Manage.*, vol. 166, pp. 758–770, Jun. 2018, doi: 10.1016/j.enconman.2018.04.005.

[42] S. Radpour, E. Gemechu, M. Ahiduzzaman, and A. Kumar, "Developing a framework to assess the long-term adoption of renewable energy technologies in the electric power sector: The effects of carbon price and economic incentives," *Renew. Sustain. Energy Rev.*, vol. 152, Dec. 2021, Art. no. 111663, doi: 10.1016/j.rser.2021.111663.

[43] M. Hájek, J. Zimmermannová, K. Helman, and L. Rozenský, "Analysis of carbon tax efficiency in energy industries of selected EU countries," *Energy Policy*, vol. 134, Nov. 2019, Art. no. 110955, doi: 10.1016/j.enpol.2019.110955.

[44] L. Ji, Y. Wu, Y. Xie, L. Sun, and G. Huang, "An integrated framework for feasibility analysis and optimal management of a neighborhood-scale energy system with rooftop PV and waste-to-energy technologies," *Energy Sustain. Develop.*, vol. 70, pp. 78–92, Oct. 2022, doi: 10.1016/j.esd.2022.07.012.

[45] A. K. S. Maisanam, A. Biswas, and K. K. Sharma, "Integrated socio-environmental and techno-economic factors for designing and sizing of a sustainable hybrid renewable energy system," *Energy Convers. Manage.*, vol. 247, Nov. 2021, Art. no. 114709, doi: 10.1016/j.enconman.2021.114709.

[46] J. Liu, N. Gong, and J. Qin, "How would the carbon tax on energy commodities affect consumer welfare? Evidence from China's household energy consumption system," *J. Environ. Manage.*, vol. 317, Sep. 2022, Art. no. 115466, doi: 10.1016/j.jenvman.2022.115466.

[47] W. Liu, Y. Li, T. Liu, M. Liu, and H. Wei, "How to promote low-carbon economic development? A comprehensive assessment of carbon tax policy in China," *Int. J. Environ. Res. Public Health*, vol. 18, no. 20, p. 10699, Oct. 2021, doi: 10.3390/ijerph182010699.

[48] X. Zhu, B. Liao, and S. Yang, "An optimal incentive policy for residential prosumers in Chinese distributed photovoltaic market: A Stackelberg game approach," *J. Cleaner Prod.*, vol. 308, Jul. 2021, Art. no. 127325, doi: 10.1016/j.jclepro.2021.127325.

[49] *Research Study on Reuse and Recycling of Batteries Employed in Electric Vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries*, Kelleher Environmental, Toronto, ON, Canada, 2019, p. 206.

[50] P. Ifaei, A. S. T. Charmchi, J. Loy-Benitez, R. J. Yang, and C. Yoo, "A data-driven analytical roadmap to a sustainable 2030 in South Korea based on optimal renewable microgrids," *Renew. Sustain. Energy Rev.*, vol. 167, Oct. 2022, Art. no. 112752, doi: 10.1016/j.rser.2022.112752.

[51] X. Zhao, J. Yao, C. Sun, and W. Pan, "Impacts of carbon tax and tradable permits on wind power investment in China," *Renew. Energy*, vol. 135, pp. 1386–1399, May 2019, doi: 10.1016/j.renene.2018.09.068.

[52] E. Martelli, M. Freschini, and M. Zatti, "Optimization of renewable energy subsidy and carbon tax for multi energy systems using bilevel programming," *Appl. Energy*, vol. 267, Jun. 2020, Art. no. 115089, doi: 10.1016/j.apenergy.2020.115089.

[53] R. Fallahifar and M. Kalantar, "Optimal planning of lithium ion battery energy storage for microgrid applications: Considering capacity degradation," *J. Energy Storage*, vol. 57, Jan. 2023, Art. no. 106103, doi: 10.1016/j.est.2022.106103.

[54] K. Gugler, A. Haxhimusa, and M. Liebensteiner, "Effectiveness of climate policies: Carbon pricing vs. subsidizing renewables," *J. Environ. Econ. Manage.*, vol. 106, Mar. 2021, Art. no. 102405, doi: 10.1016/j.jeem.2020.102405.

[55] G. Yin, L. Zhou, M. Duan, W. He, and P. Zhang, "Impacts of carbon pricing and renewable electricity subsidy on direct cost of electricity generation: A case study of China's provincial power sector," *J. Cleaner Prod.*, vol. 205, pp. 375–387, Dec. 2018, doi: 10.1016/j.jclepro.2018.09.108.

[56] M. Philippot, D. Costa, M. S. Hosen, A. Senécat, E. Brouwers, E. Nanini-Maury, J. Van Mierlo, and M. Messagie, "Environmental impact of the second life of an automotive battery: Reuse and repurpose based on ageing tests," *J. Cleaner Prod.*, vol. 366, Sep. 2022, Art. no. 132872, doi: 10.1016/j.jclepro.2022.132872.

[57] Z. Song, M. S. Nazir, X. Cui, I. A. Hiskens, and H. Hofmann, "Benefit assessment of second-life electric vehicle lithium-ion batteries in distributed power grid applications," *J. Energy Storage*, vol. 56, Dec. 2022, Art. no. 105939, doi: 10.1016/j.est.2022.105939.

[58] J. Abrell, M. Kosch, and S. Rausch, "Carbon abatement with renewables: Evaluating wind and solar subsidies in Germany and Spain," *J. Public Econ.*, vol. 169, pp. 172–202, Jan. 2019, doi: 10.1016/j.jpubeco.2018.11.007.

[59] Y. He, Y. Pang, X. Li, and M. Zhang, "Dynamic subsidy model of photovoltaic distributed generation in China," *Renew. Energy*, vol. 118, pp. 555–564, Apr. 2018, doi: 10.1016/j.renene.2017.11.042.

[60] H. Tang and S. Wang, "Life-cycle economic analysis of thermal energy storage, new and second-life batteries in buildings for providing multiple flexibility services in electricity markets," *Energy*, vol. 264, Feb. 2023, Art. no. 126270, doi: 10.1016/j.energy.2022.126270.

[61] M. Terkes, Z. Öztürk, A. Demirci, and S. M. Tercan, "Optimal sizing and feasibility analysis of second-life battery energy storage systems for community microgrids considering carbon reduction," *J. Cleaner Prod.*, vol. 421, Oct. 2023, Art. no. 138507.

[62] D. D. Alijanov and N. A. O. Topvoldiyev, ''Physical and technical fundamentals of photoelectric solar panels energy,'' *Theor. Appl. Sci.*, vol. 108, no. 4, pp. 501–505, Apr. 2022, doi: 10.15863/TAS.2022.04.108.55.

[63] M. Terkes, A. Demirci, and E. Gokalp, ''An evaluation of optimal sized second-life electric vehicle batteries improving technical, economic, and environmental effects of hybrid power systems,'' *Energy Convers. Manage.*, vol. 291, Sep. 2023, Art. no. 117272, doi: 10.1016/j.enconman.2023.117272.

[64] J. F. Manwell and J. G. McGowan, ''Lead acid battery storage model for hybrid energy systems,'' *Sol. Energy*, vol. 50, no. 5, pp. 399–405, May 1993, doi: 10.1016/0038-092X(93)90060-2.

[65] *Battery Lifetime Analysis and Simulation Tool Suite*, National Renewable Energy Laboratory (NREL), Golden, CO, USA, Dec. 2014.

[66] K. Smith, M. Earleywine, E. Wood, J. Neubauer, and A. Pesaran, ''Comparison of plug-in hybrid electric vehicle battery life across geographies and drive cycles,'' in *Proc. SAE Tech. Paper Ser.*, Apr. 2012, pp. 1–11, doi: 10.4271/2012-01-0666.

[67] E. E. E. Ahmed and A. Demirci, ''Assessment of overvoltage and power losses in low voltage distribution networks with high photovoltaics penetration based on prosumers' self-consumption,'' in *Proc. Int. Congr. Hum.-Comput. Interact., Optim. Robotic Appl. (HORA)*, Jun. 2022, pp. 1–4, doi: 10.1109/HORA55278.2022.9800001.

[68] World Bank Group. (2016). *Global Solar Atlas*. Accessed: Jul. 1, 2023. [Online]. Available: https://globalsolaratlas.info/downloads/iran?c=32.62087,45.087891,5

[69] A. Demirci, Z. Ozturk, S. M. Tercan, and I. Nakir, ''Determination of photovoltaic inverter ratio minimizing energy clipping for electric vehicle charging station under different solar radiations,'' in *Proc. Int. Congr. Hum.-Comput. Interact., Optim. Robotic Appl. (HORA)*, Jun. 2022, pp. 1–6, doi: 10.1109/HORA55278.2022.9799890.

[70] Z. Ozturk, A. Demirci, S. Tosun, and A. Ozturk, ''Technic and economic effects of changes in the location of industrial facilities in industrializing regions on power systems,'' in *Proc. 13th Int. Conf. Electr. Electron. Eng. (ELECO)*, Nov. 2021, pp. 11–17, doi: 10.23919/ELECO54474.2021.9677827.

[71] M. Terkes, S. M. Tercan, A. Demirci, and E. Gokalp, ''An evaluation of renewable fraction using energy storage for electric vehicle charging station,'' in *Proc. Int. Congr. Hum.-Comput. Interact., Optim. Robotic Appl. (HORA)*, Jun. 2022, pp. 1–10, doi: 10.1109/HORA55278.2022.9800091.

[72] A. Demirci, Z. Öztürk, and S. M. Tercan, ''Decision-making between hybrid renewable energy configurations and grid extension in rural areas for different climate zones,'' *Energy*, vol. 262, Jan. 2023, Art. no. 125402, doi: 10.1016/j.energy.2022.125402.

[73] A. Demirci, O. Akar, and Z. Ozturk, ''Technical-environmental-economic evaluation of biomass-based hybrid power system with energy storage for rural electrification,'' *Renew. Energy*, vol. 195, pp. 1202–1217, Aug. 2022, doi: 10.1016/j.renene.2022.06.097.

[74] W. J. Cole, D. Greer, P. Denholm, A. W. Frazier, S. Machen, T. Mai, N. Vincent, and S. F. Baldwin, ''Quantifying the challenge of reaching a 100% renewable energy power system for the United States,'' *Joule*, vol. 5, no. 7, pp. 1732–1748, Jul. 2021, doi: 10.1016/j.joule.2021.05.011.

[75] A. Khosravani, E. Safaei, M. Reynolds, K. E. Kelly, and K. M. Powell, ''Challenges of reaching high renewable fractions in hybrid renewable energy systems,'' *Energy Rep.*, vol. 9, pp. 1000–1017, Dec. 2023, doi: 10.1016/j.egyr.2022.12.038.

ALPASLAN DEMIRCI received the B.Sc. and M.Sc. degrees in electrical education from Marmara University, İstanbul, Turkey, in 2007 and 2011, respectively, the B.Sc. degree in electrical and electronics engineering from Sakarya University, Turkey, in 2017, and the Ph.D. degree in electrical engineering from the Graduate School of Science and Engineering, Yıldız Technical University (YTU), İstanbul, in 2023. From 2012 to 2016, he was a Lecturer with the Department of Electricity and Energy, YTU, where he has been a Lecturer with the Electrical Engineering Department, since 2016. His research interests include power system optimization methods, distributed renewable energy systems, energy economics, electric vehicles, and energy storage systems. He has published several papers related to his research areas.