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Qayta tiklanuvchi energiya manbalari va energiya saqlash tizimlari asosida sanoat korxonalari elektr ta'minotining energiya samaradorligini oshirish

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Annotatsiya. Maqolada sanoat korxonalari elektr ta'minotining energiya samaradorligini quyosh fotoelektrik stansiyalari (FES) va batareyali energiya saqlash tizimi (BESS) asosida oshirish masalasi tadqiq etilgan. Yuklama, FES generatsiyasi va BESS ning matematik modellari tuzilib, yillik elektr energiya xarajatini minimallashtirish masalasi qo'yilgan. Cho'qqi quvvati 2 MVt bo'lgan shartli korxona uchun uch ssenariy (faqat tarmoq; tarmoq + FES; tarmoq + FES + BESS) LCOE, LCOS, oddiy qaytarilish muddati va CO₂ chiqindisi ko'rsatkichlari bo'yicha solishtirilgan. FES yillik xarajatni taxminan 19,9 %, FES va BESS birgalikda 25,5 % ga kamaytirishi, CO₂ chiqindisi esa 25 % dan ortiq qisqarishi aniqlangan. BESS ning iqtisodiy samarasi asosan quvvat uchun to'lov cho'qqisini kesishga bog'liqligi ko'rsatilgan.

Kalit so'zlar: energiya samaradorligi, sanoat elektr ta'minoti, quyosh energiyasi, energiya saqlash tizimi, BESS, cho'qqini kesish, LCOE, LCOS.

Abstract. This paper investigates improving the energy efficiency of industrial power supply by means of solar photovoltaic (PV) plants and battery energy storage systems (BESS). Mathematical models of the load, PV generation and BESS are developed, and an annual electricity cost minimisation problem is formulated. Three scenarios (grid only; grid + PV; grid + PV + BESS) are compared for an illustrative plant with a 2 MW peak demand in terms of LCOE, LCOS, simple payback period and CO₂ emissions. PV reduces the annual cost by about 19.9 %, PV with BESS by 25.5 %, and CO₂ emissions fall by more than 25 %. The economic value of BESS is shown to be driven mainly by demand-charge reduction.

Keywords: energy efficiency, industrial power supply, solar PV, energy storage, BESS, peak shaving, LCOE, LCOS.

Аннотация. В статье исследуется повышение энергоэффективности электроснабжения промышленных предприятий на основе солнечных фотоэлектрических станций (ФЭС) и систем накопления энергии (BESS). Разработаны математические модели нагрузки, генерации ФЭС и BESS, сформулирована задача минимизации годовых затрат на электроэнергию. Для условного предприятия с пиковой нагрузкой 2 МВт сопоставлены три сценария (только сеть; сеть + ФЭС; сеть + ФЭС + BESS) по показателям LCOE, LCOS, простого срока окупаемости и выбросов CO₂. ФЭС снижает годовые затраты примерно на 19,9 %, ФЭС совместно с BESS на 25,5 %, выбросы CO₂



сокращаются более чем на 25 %. Экономический эффект BESS определяется главным образом снижением платы за максимальную мощность.

Ключевые слова: энергоэффективность, промышленное электроснабжение, солнечная энергия, накопители энергии, BESS, срезка пиков, LCOE, LCOS.

KIRISH

Sanoat sektori O'zbekistonda elektr energiyasining eng yirik iste'molchilaridan biri bo'lib, uning energiya sig'imi rivojlangan davlatlarga nisbatan yuqori [2, 3]. Elektr tarmoqlarida texnik yo'qotishlar va yuklamaning notekisligi korxonalar xarajatini oshiradi. Mamlakat 2030-yilgacha «yashil» iqtisodiyotga o'tish strategiyasini qabul qilgan va qayta tiklanuvchi energiya ulushini oshirishni maqsad qilgan [1]. Dunyoda quyosh FES narxi so'nggi o'n yillikda keskin pasaygan [4, 5], batareya narxi ham tajriba egri chizig'i bo'yicha kamayib bormoqda [11, 12].

Muammo. Sanoat korxonalari uchun FES va BESS ni birgalikda loyihalash bo'yicha ishlarning aksariyati umumiy sharh xarakteriga ega yoki xorijiy tarif sharoitiga mo'ljallangan. Markaziy Osiyo, jumladan O'zbekiston tarif va iqlim sharoitida korxona darajasidagi aniq texnik-iqtisodiy baholar yetarli emas (tadqiqot bo'shlig'i).

Maqsad: sanoat korxonasi elektr ta'minotida FES va BESS dan foydalanishning energetik va iqtisodiy samaradorligini baholash metodikasini ishlab chiqish.

Vazifalar: (1) yuklama, FES va BESS modellarini tuzish; (2) yillik xarajetni minimallashtirish masalasini qo'yish; (3) uch ssenariyni LCOE, LCOS, qaytarilish muddati va CO₂ bo'yicha solishtirish; (4) sezgirlik tahlilini o'tkazish.

Ilmiy yangilik: sanoat korxonasi uchun FES va BESS ning birgalikdagi samarasi o'z iste'moli ulushi, quvvat uchun to'lovni kesish va LCOS ko'rsatkichlari bilan yagona metodikada baholanadi hamda O'zbekiston sharoitiga moslashtirilgan sezgirlik tahlili beriladi.

ADABIYOTLAR TAHLILI

Jahon tadqiqotlari. Lund qayta tiklanuvchi manbalar ulushi oshganda tizim darajasida moslashuvchanlik zarurligini ko'rsatgan [6]. Dunn va boshq. tarmoq uchun energiya saqlash texnologiyalarini qiyoslab, batareylarning keng qo'llanish istiqbolini asoslagan [7]. Luo va boshq. saqlash texnologiyalarining texnik ko'rsatkichlari va tizim ishidagi qo'llanilishini tizimlashtirgan [8]. Kousksou va boshq. saqlash tizimlarining qo'llanish sohalari va to'siqlarini tahlil qilgan [9]. Hesse va boshq. statsionar litiy-ion tizimlarini loyihalash masalalarini ko'rib chiqqan [10]. Schmidt va boshq. saqlash narxining tajriba egri chizig'i bo'yicha pasayishini [11] va LCOS prognozini [12] bergan. Pfenninger va Staffell FES chiqishini ko'p yillik soatlik ma'lumotlar asosida modellashtirish uslubini taklif qilgan [13]. Xu va boshq. batareya eskirish xarajatini optimallashtirishga kiritgan [14]. PNNL hisoboti saqlash tizimlari narxi va ko'rsatkichlarini umimlashtiradi [15].



O'zbekiston va MDH tadqiqotlari. O'zbekiston olimlari asosan quyosh resursini baholash, FES ni tarmoqqa ulash va elektr ta'minot tizimlarida energiya tejash masalalarini o'rgangan [18–22] Hukumat hujjatlari maqsad va tariflar asosini belgilaydi [1].

1-jadval. Adabiyotlarning qiyosiy tahlili

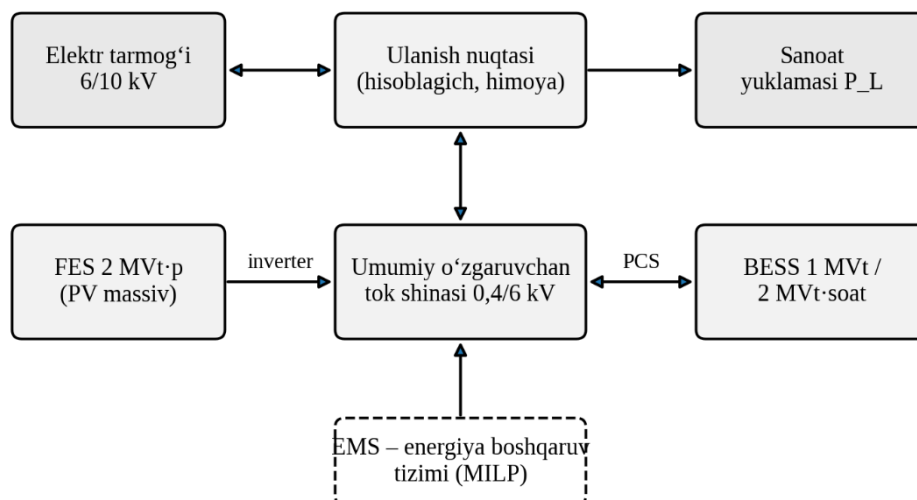
Manba	Yo'nalish	Qamrov	Cheklov
[6]	Strategiya	Tizim darajasi	Korxona darajasi yo'q
[7–9]	Saqlash sharhi	Texnologiyalar qiyosi	Aniq tarif hisobi yo'q
[11, 12]	Narx prognozi	LCOS, tajriba egri chizig'i	Sanoat yuklamasi yo'q
[13]	FES modellash	Soatlik ma'lumot	Faqat Yevropa
[14]	Optimallashtirish	Eskirish narxi	Sanoat iste'molchisi emas
[18–22]	Mahalliy ishlar	Resurs va ulash	FES + BESS birga emas

Tahlil sanoat korxonasi uchun FES va BESS ni yagona metodikada, quvvat to'lovi va LCOS bilan birga baholaydigan, O'zbekiston sharoitiga mo'ljallangan ishlar kamligini ko'rsatadi.

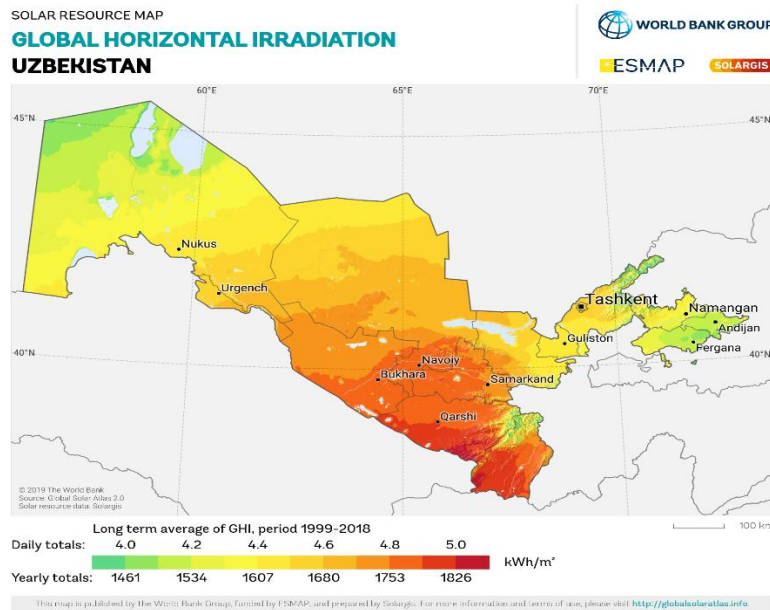
METODOLOGIYA

Yuklama va resurs

Korxona yuklamasi $P_L(t)$ soatlik (8760 soat) grafik bilan beriladi: ikki-uch smenali ishlab chiqarish uchun kunduzgi yuqori, tungi pasaygan profil olinadi. Quyosh resursi Global Solar Atlas ma'lumotlari asosida olinadi [16] (2-rasm). Tizimning strukturaviy sxemasi 1-rasmga keltirilgan.



1-rasm. Gibrid elektr ta'minot tizimining strukturaviy sxemasi



2-rasm. O'zbekistonda quyosh energiyasi potentsiali (PVOUT) [16]

FES va shamol generatsiyasi modeli

Fotoelektrik stansiyaning quvvati:

$$P_{PV}(t) = P_{nom} \frac{G(t)}{G_{STC}} [1 - \gamma(T_c(t) - 25)] \eta_{inv} \quad (1)$$

bu yerda $P_{PV}(t)$ – FES ning t vaqtdagi chiqish quvvati, kVt; P_{nom} – o'rnatilgan (pasport) quvvat, kVt·p; $G(t)$ – qiyalangan sirdagi nurlanish zichligi, Vt/m²; $G_{STC} = 1000$ Vt/m² – standart sinov sharoitidagi nurlanish zichligi; γ – quvvatning harorat koeffitsiyenti, 1/°C (kristalli kremniy uchun taxminan 0,004); $T_c(t)$ – fotoelektrik modul harorati, °C; η_{inv} – inverterning FIK.

Shamol agregati (resurs yetarli bo'lganda) quvvati:

$$P_W(t) = \begin{cases} 0, & v(t) < v_{ci} \text{ yoki } v(t) > v_{co}, \\ 1/2 \rho A C_p v^3(t), & v_{ci} \leq v(t) \leq v_r, \\ P_r, & v_r < v(t) \leq v_{co}, \end{cases} \quad (2)$$

bu yerda ρ – havo zichligi, kg/m³; A – shamol g'ildiragi tarashlagan yuza, m²; C_p – shamol energiyasidan foydalanish koeffitsiyenti; v – shamol tezligi, m/s; v_{ci} , v_r , v_{co} – ishga tushish, nominal va uzish tezliklari, m/s; P_r – nominal quvvat, kVt. Quyidagi hisobda mavjud shamol resursi FES ga nisbatan cheklangan deb qabul qilinib, shamol generatsiyasi hisobga olinmagan.

BESS modeli

Batareyaning zaryad holati (SOC) va cheklovlari:

$$SOC(t+1) = SOC(t) + \frac{[\eta_c P_c(t) - P_d(t)/\eta_d] \Delta t}{E_{nom}} \quad (3)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max}, \quad 0 \leq P_c(t) \leq P_{BESS} u(t), \quad 0 \leq P_d(t) \leq P_{BESS} [1 - u(t)], \quad u(t) \in \{0,1\} \quad (4)$$

bu yerda SOC – zaryad holati (nisbiy birlik); η_c , η_d – zaryad va razryad FIK; P_c , P_d – zaryad va razryad quvvati, kVt; E_{nom} – nominal energiya sig'imi, kVt·soat;



P_{BESS} – BESS ning nominal quvvati, kVt; $u(t)$ – ikkilik o'zgaruvchi (1 – zaryad, 0 – razryad), zaryad va razryadning bir vaqtda sodir bo'lishini istisno qiladi; Δt – hisob qadami, soat. Batareya eskirishi xarajati zaryad–razryad tsikllari soni va chuqurligi bo'yicha hisobga olinadi [14].

Optimallashtirish masalasi

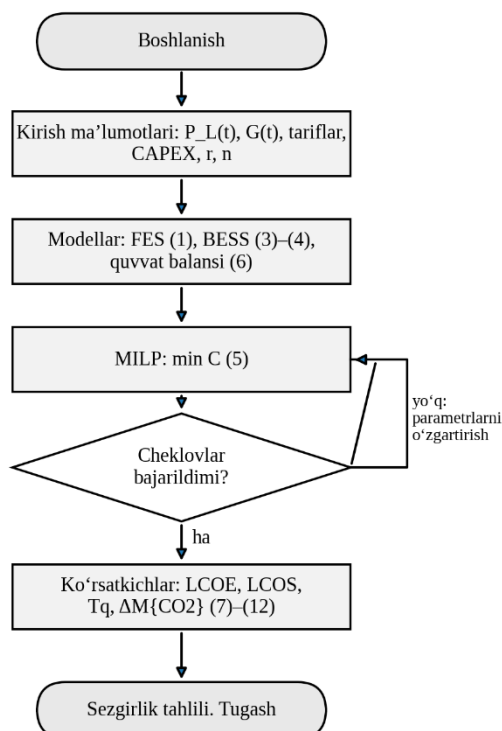
Maqsad funksiyasi – yillik elektr ta'minoti xarajatini minimallashtirish:

$$\min C = \sum_{t=1}^{8760} c_e(t) P_g(t) \Delta t + \sum_{m=1}^{12} c_d \max_{t \in T_m} P_g(t) + CRF \cdot CAPEX + C_{OM} \quad (5)$$

quyidagi quvvat balansi cheklovi ostida:

$$P_g(t) + P_{PV}(t) + P_d(t) = P_L(t) + P_c(t) + P_{exp}(t) \quad (6)$$

bu yerda $c_e(t)$ – energiya tarifi, USD/(kVt·soat); c_d – maksimal quvvat uchun to'lov, USD/(kVt·oy); P_g – tarmoqdan olinadigan quvvat, kVt; T_m – m -oyga tegishli soatlar to'plami; P_L – yuklama quvvati, kVt; P_{exp} – tarmoqqa berilgan yoki kesilgan ortiqcha quvvat, kVt; $CRF \cdot CAPEX$ – yillik kapital xarajat, USD; C_{OM} – yillik ekspluatatsiya xarajati, USD. Masala aralash butun sonli chiziqli dasturlash (MILP) usulida yechiladi. Algoritm 3-rasmda ko'rsatilgan.



3-rasm. Optimallashtirish algoritmining blok-sxemasi

Samaradorlik ko'rsatkichlari

Keltirilgan energiya narxi (LCOE) va saqlash tizimining keltirilgan narxi (LCOS):

$$LCOE = \frac{CRF \cdot CAPEX_{PV} + C_{OM,PV}}{E_{PV}} \quad (7)$$



$$LCOS = \frac{CRF \cdot CAPEX_{BESS} + C_{OM,BESS}}{E_{dis}} \quad (8)$$

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (9)$$

bu yerda CRF – kapitalni qaytarish koeffitsiyenti; r – diskont stavka; n – xizmat muddati, yil; E_{PV} – FES ning yillik ishlab chiqargan energiyasi, kVt·soat; E_{dis} – BESS ning yillik razryad energiyasi, kVt·soat. Qo‘shimcha ko‘rsatkichlar – o‘z iste‘moli ulushi, oddiy qaytarilish muddati va CO₂ chiqindisining kamayishi:

$$SC = \frac{E_{PV,is}}{E_{PV}} \cdot 100\% \quad (10)$$

$$T_q = \frac{CAPEX}{\Delta C_{yil}} \quad (11)$$

$$\Delta M_{CO_2} = e_g(E_{PV,is} + E_{dis} - E_c) \quad (12)$$

bu yerda $E_{PV,is}$ – korxonada bevosita iste‘mol qilingan FES energiyasi, kVt·soat; ΔC_{yil} – yillik sof tejam, USD; e_g – tarmoq elektr energiyasining CO₂ emissiya omili, t/(MVt·soat); E_c – BESS ni zaryadlash uchun sarflangan energiya, kVt·soat [4, 15, 17].

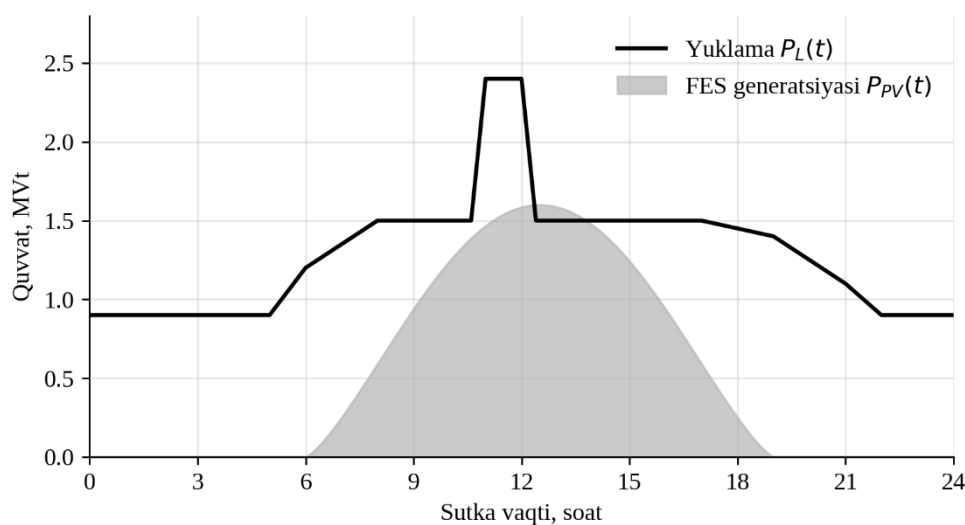
NATIJALAR VA MUHOKAMA

Hisob shartli korxona uchun bajarildi (shartli hisob-kitob). Kirish parametrlari 2-jadvalda keltirilgan; ular xalqaro ko‘rsatkichlarga yaqin tanlangan [4, 11, 15, 17], biroq O‘zbekiston tarifi va narxlari bilan almashtirilishi shart.

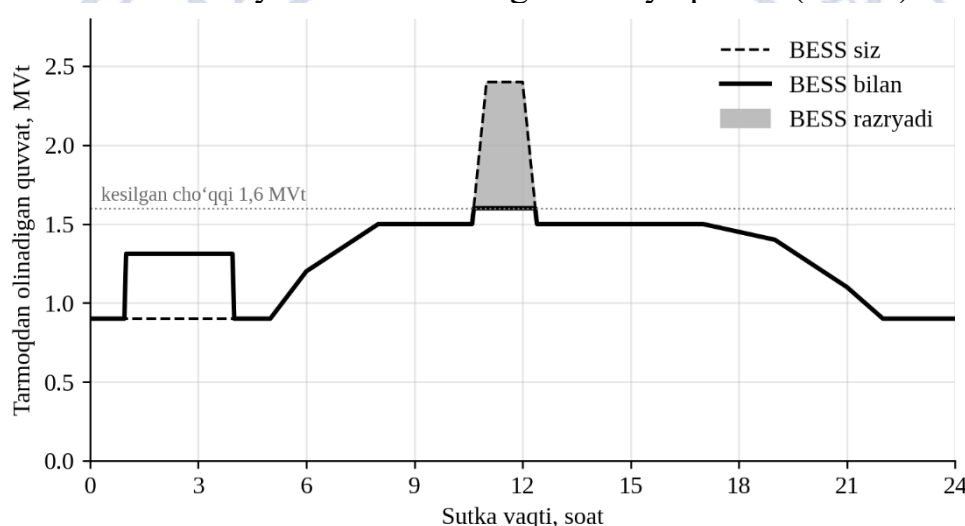
2-jadval. Shartli kirish parametrlari

Parametr	Qiymat
Yillik iste‘mol / cho‘qqi quvvat	12 GVt·soat / 2,4 MVt
FES quvvati, solishtirma ishlab chiqarish	2 MVt·p, 1600 kVt·soat/kVt·p
FES CAPEX / O&M	600 USD/kVt·p / 12 USD/(kVt·p·yil)
BESS	1 MVt / 2 MVt·soat; CAPEX 350 USD/(kVt·soat); FIK 88 %; 300 tsikl/yil; 10 yil
Energiya tarifi / quvvat to‘lovi	0,08 USD/(kVt·soat) / 5 USD/(kVt·oy)
Tarif farqi (cho‘qqi–tun)	0,03 USD/(kVt·soat)
Diskont stavka, FES xizmat muddati	8 %, 25 yil
Emissiya omili	0,5 tCO ₂ /(MVt·soat)

Sutkalik yuklama va FES generatsiya profili 4-rasmda, BESS yordamida cho‘qqini kesish esa 5-rasmda ko‘rsatilgan (profilar tushuntirish uchun shartli tuzilgan).



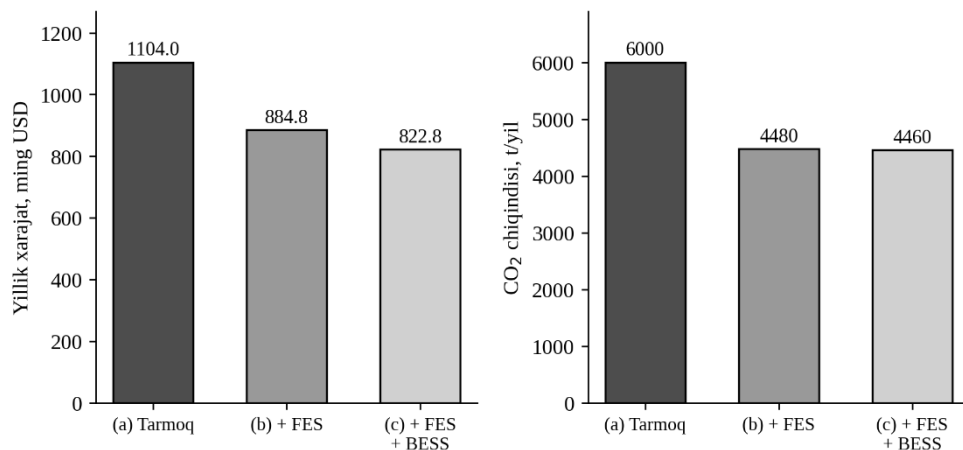
4-rasm. Sutkalik yuklama va FES generatsiya profili (shartli)



5-rasm. BESS yordamida yuklama cho'qqisini kesish (shartli)

3-jadval. Ssenariylar natijalari (shartli)

Ko'rsatkich	(a) Tarmoq	(b) + FES	(c) + FES + BESS
Yillik xarajat, ming USD	1104,0	884,8	822,8
Tejam, %	—	19,9	25,5
CO ₂ , t/yil	6000	4480	≈ 4460
Investitsiya, ming USD	0	1200	1900
Qaytarilish muddati, yil	—	5,5	6,8
LCOE (FES) / LCOS (BESS), USD/(kVt·soat)	—	0,043	0,043 / 0,206



6-rasm. Ssenariylar bo'yicha yillik xarajat va CO₂ chiqindisi

MUHOKAMA.

FES kunduzgi yuklama bilan mos tushgani uchun o'z iste'moli ulushi yuqori (taxminan 95 %), LCOE esa tarmoq tarifidan ancha past, shuning uchun FES asosiy tejam manbai hisoblanadi. BESS ning o'zi alohida taxminan 11 yilda qaytadi: LCOS (0,206 USD/(kVt·soat)) tarif farqidan (0,03 USD/(kVt·soat)) yuqori, shuning uchun u arbitraj hisobiga emas, asosan maksimal quvvat uchun to'lovni kamaytirish (0,8 MVt kesish, yiliga 48 ming USD) hisobiga oqlanadi. Bu xulosa saqlash tizimlari narxi va muddati bo'yicha global tahlillardagi tendensiyalarga mos keladi [11, 12, 15].

Sezgirlik tahlili. FES uchun oddiy qaytarilish muddati tarif 20 % ga pasayganda 7,0 yilga uzayadi, 20 % ga oshganda 4,5 yilga qisqaradi. BESS uchun CAPEX 30 % kamayganda 7,9 yil, 30 % oshganda 14,7 yil; quvvat to'lovi 10 USD/(kVt·oy) ga ko'tarilsa, BESS qaytarilish muddati 6,4 yilgacha qisqaradi. Demak, tarif tuzilmasi, ayniqsa quvvat uchun to'lov, loyiha samaradorligining asosiy omilidir.

XULOSA VA AMALIY TAVSIYALAR

Shartli 2 MVt cho'qqi quvvatli korxona uchun 2 MVt·p FES yillik elektr xarajatini 1104 ming USD dan 885 ming USD gacha (–19,9 %), FES va 1 MVt / 2 MVt·soat BESS birgalikda 823 ming USD gacha (–25,5 %) kamaytiradi. FES ning LCOE si taxminan 0,043 USD/(kVt·soat), BESS ning LCOS i 0,206 USD/(kVt·soat) bo'lib, FES loyihasi 5,5 yilda, FES + BESS 6,8 yilda qaytadi. CO₂ chiqindisi yiliga 6000 t dan taxminan 4460 t gacha (25 % dan ortiq) kamayadi. BESS asosan quvvat to'lovi cho'qqisini kesish hisobiga oqlanadi, shuning uchun uning samaradorligi tarif tuzilmasiga eng sezgir.

Tavsiyalar: (1) avval FES ni kunduzgi yuklamaga mos o'lchamda o'rnatish; (2) BESS ni faqat quvvat uchun to'lov yoki cho'qqi tarifi mavjud bo'lganda va CAPEX ko'rsatilgan chegarada bo'lganda qo'shish; (3) loyihadan oldin



korxonaning soatlik yuklama ma'lumotini o'lchash; (4) hisoblarni haqiqiy tarif va narxlar bilan qayta bajarish.

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