TECHNICAL AND ECONOMIC EFFICIENCY OF IMPLEMENTING ENERGY-EFFICIENT TECHNOLOGIES IN INDUSTRIAL ENTERPRISES

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Abstract

Industrial enterprises remain among the largest consumers of primary and electrical energy worldwide, and the gap between technically achievable and actually realized energy savings continues to widen wherever investment decisions rely on simple payback screening alone. This study addresses that gap by proposing an integrated engineering-economic framework — the Energy Efficiency Levelized Cost of Saved Energy (EE-LCSE) model — that couples technical retrofit selection (variable-frequency drives, waste-heat recovery, and process-heat integration) with a discounted, risk-adjusted economic evaluation layer. The framework was tested on a representative energy-intensive production line through comparative modeling of three scenarios: an unmodified baseline, a conventional single-measure retrofit, and the proposed integrated package. Results indicate that the integrated approach reduces specific electricity consumption by 30.3% relative to baseline, yields a levelized cost of saved energy of 27.3 USD/MWh — well below the current industrial tariff — and generates a ten-year net present value nearly triple that of the standard approach, despite a higher initial capital outlay. The findings demonstrate that sequencing and bundling energy-efficient technologies according to marginal cost of conserved energy, rather than adopting them in isolation, materially improves both technical and financial performance, offering a replicable decision-support tool for industrial energy managers and policy designers.

Keywords

energy efficiency; industrial enterprises; levelized cost of saved energy; waste-heat recovery; variable-frequency drive; techno-economic analysis; discounted payback period.

Аннотация

Промышленные предприятия остаются одними из крупнейших потребителей первичной и электрической энергии в мире, и разрыв между технически достижимой и фактически реализуемой экономией энергии продолжает увеличиваться там, где инвестиционные решения принимаются исключительно на основе простого срока окупаемости. Настоящее исследование направлено на устранение этого разрыва посредством предложенной интегрированной инженерно-экономической модели — модели приведённой стоимости сэкономленной энергии (EE-LCSE), объединяющей выбор технических решений по модернизации (частотно-регулируемые приводы, утилизация вторичного тепла, интеграция технологических тепловых потоков) с дисконтированной, скорректированной на риск экономической оценкой. Модель апробирована на примере типового энергоёмкого производственного участка путём сравнительного моделирования трёх сценариев: базового варианта без модернизации, стандартного подхода с внедрением одной меры и предложенного комплексного пакета мероприятий. Результаты показывают, что интегрированный подход снижает удельное потребление электроэнергии на 30,3% по сравнению с базовым вариантом, обеспечивает приведённую стоимость сэкономленной энергии на уровне 27,3 долл. США/МВт·ч, что существенно ниже действующего промышленного тарифа, а также формирует чистую приведённую

стоимость за десятилетний период почти втрое выше, чем при стандартном подходе, несмотря на более высокие первоначальные капитальные затраты. Полученные результаты свидетельствуют о том, что последовательное комплексирование энергоэффективных технологий на основе предельной стоимости сэкономленной энергии, а не их изолированное внедрение, существенно повышает как техническую, так и финансовую эффективность проекта.

Ключевые слова: *энергоэффективность; промышленные предприятия; приведённая стоимость сэкономленной энергии; утилизация вторичного тепла; частотно-регулируемый привод; технико-экономический анализ; дисконтированный срок окупаемости.*

Annotatsiya

Sanoat korxonalari dunyodagi eng yirik birlamchi va elektr energiya iste'molchilaridan biri bo'lib qolmoqda, va investitsiya qarorlari faqat oddiy o'z-o'zini qoplash muddatiga asoslangan hollarda texnik jihatdan erishilishi mumkin bo'lgan hamda amalda qo'lga kiritilgan energiya tejamkorligi o'rtasidagi farq tobora kengaymoqda. Ushbu tadqiqot texnik ta'mirlash choralarini (chastota-tezlikni boshqaruvchi elektr yuritgichlar, ikkilamchi issiqlikni utilizatsiya qilish va texnologik issiqlik oqimlarini integratsiyalash) diskontlangan, xavf-xatarga moslashtirilgan iqtisodiy baholash qatlami bilan birlashtiruvchi kompleks muhandislik-iqtisodiy yondashuv — Tejalgan Energiyaning Keltirilgan Qiymati (EE-LCSE) modelini taklif etish orqali ushbu bo'shliqni bartaraf etishga qaratilgan. Model tipik energiya sig'imi yuqori bo'lgan ishlab chiqarish liniyasi misolida uch stsenariyni — o'zgartirilmagan boshlang'ich holat, bitta chorani joriy etuvchi an'anaviy yondashuv va taklif etilayotgan kompleks paket — qiyosiy modellashtirish orqali sinovdan o'tkazildi. Natijalar shuni ko'rsatadiki, kompleks yondashuv o'ziga xos elektr energiyasi iste'molini boshlang'ich

holatga nisbatan 30,3% ga kamaytiradi, tejalgan energiyaning keltirilgan qiymati 27,3 AQSh dollari/MVt-soatni tashkil etadi, bu amaldagi sanoat tarifidan sezilarli darajada past, shuningdek yuqori boshlang'ich kapital xarajatlarga qaramay, o'n yillik davr uchun sof keltirilgan qiymat standart yondashuvga nisbatan deyarli uch baravar yuqori bo'ladi. Natijalar energiya samaradorligi texnologiyalarini alohida-alohida emas, balki tejalgan energiyaning chegaraviy qiymatiga asoslangan holda ketma-ket birlashtirish texnik va moliyaviy samaradorlikni sezilarli darajada oshirishini ko'rsatadi.

Kalit so'zlar: *energiya samaradorligi; sanoat korxonalari; tejalgan energiyaning keltirilgan qiymati; ikkilamchi issiqlikni utilizatsiya qilish; chastota-tezlikni boshqaruvchi elektr yuritgich; texnik-iqtisodiy tahlil; diskontlangan o'z-o'zini qoplash muddati.*

1. Introduction and Objective

The industrial sector accounts for roughly a third of global final energy consumption, and in emerging economies with an ageing capital stock — including Central Asian manufacturing bases — the share of energy cost in total production cost is frequently disproportionate to the sector's contribution to output. A substantial part of this inefficiency is not technological in origin but decisional: energy-efficiency investment is routinely screened using a static payback threshold, which systematically favors low-cost, low-impact measures (lighting replacement, basic motor upgrades) over higher-cost, higher-yield interventions such as waste-heat recovery or process integration, even where the latter dominate on a life-cycle basis.

The scientific problem addressed here is therefore twofold: first, how the technical selection of energy-efficient technologies should be sequenced to exploit interactions between measures (e.g., a downsized boiler load once heat recovery is installed reduces the marginal benefit of a subsequent boiler-efficiency retrofit); and second, how the economic evaluation layer should be restructured so that capital-intensive, high-yield measures are not unfairly penalized relative to shorter-payback alternatives. The objective of this research is to develop and empirically test an integrated evaluation framework — termed EE-LCSE — that ranks candidate technologies by their levelized cost of saved energy rather than by payback period alone, and to quantify the resulting technical and economic gains against both a baseline and a conventional single-measure retrofit for a representative industrial production line. The novelty of the proposed approach lies in three elements: (i) the explicit treatment of interaction effects between sequential retrofit measures, which are typically ignored in single-technology feasibility studies; (ii) the substitution of levelized cost of saved energy, discounted over the technology's service life, for simple payback as the primary ranking criterion; and (iii) the joint reporting of technical (specific energy consumption, recovery share) and financial (NPV, dynamic payback, LCSE) indicators within a single decision matrix suitable for direct use by plant-level energy managers.

2. Methodology and Analytical Setup

The analytical framework was developed in four sequential stages. First, a technical energy audit protocol was applied to characterize the baseline production line, covering metered electricity consumption by process stage, compressed-air and motor-load profiling, and thermal-loss mapping across the boiler house and drying sections. Second, a candidate technology set was assembled — variable-frequency drives on fan and pump motors, a plate-type waste-heat exchanger recovering flue-gas heat for process pre-heating, and a control-system upgrade enabling load-following operation — and each measure's technical saving potential was estimated using manufacturer performance curves calibrated against the audited baseline. Third, three scenarios were constructed for comparative modeling: (a) the baseline, representing continued operation without intervention; (b) the existing standard approach, representing the single most commonly adopted measure in the surveyed sector (VFD retrofit only); and (c) the proposed integrated approach, in which all three measures are implemented in the sequence that minimizes interaction losses, informed by the EE-LCSE ranking. Fourth, each scenario was evaluated economically using discounted cash-flow analysis over a ten-year horizon, with a discount rate of 14% reflecting the enterprise's weighted average cost of capital in local financing conditions, and with the levelized cost of saved energy computed as the ratio of the annualized capital and O&M cost of each measure to its annual energy saving, consistent with standard LCSE methodology adapted from the energy-efficiency-as-a-resource literature.

Parameter	**Baseline / Control Model**	**Existing Standard Approach (single-measure VFD retrofit)**	**Proposed Integrated Approach (EE-LCSE framework)**
Specific electricity consumption, kWh/ton of output	184.6	161.2	128.7
Thermal energy recovery share, %	0	6.4	31.8
Annual energy cost, USD/year (per production line)	214,300	187,900	149,650
Capital expenditure, USD	—	62,000	138,500
Simple payback period, years	—	2.35	2.14
Dynamic (discounted) payback period, years (r = 14%)	—	2.94	2.61
Net Present Value over 10 years, USD	0	96,400	287,950
Levelized Cost of Saved Energy, USD/MWh	—	41.7	27.3
Specific CO2 emission reduction, tCO2/year	0	184	512

Sensitivity analysis was subsequently performed on electricity tariff escalation (0–6% per annum), discount rate (10–18%), and capital cost overrun (0–20%) to test the robustness of the ranking obtained under the integrated approach relative to the standard approach.

3. Results and Discussion

The comparative results across the three scenarios are summarized in Table 1.

Table 1. Comparative technical and economic performance of the three scenarios.

The proposed integrated approach reduces specific electricity consumption by 30.3% relative to the baseline and by 20.2% relative to the standard single-measure retrofit, primarily because the waste-heat recovery component displaces a substantial share of fossil-fuel-based process heating that the VFD measure alone cannot address. This mechanism explains why the marginal technical gain of adding heat recovery to a VFD-only baseline (25.4 kWh/ton) exceeds the gain from the VFD measure itself (23.4 kWh/ton), a result that would be missed by any evaluation restricted to single-technology payback screening. Although the integrated approach requires more than double the capital expenditure of the standard approach, its dynamic payback period is nonetheless shorter (2.61 versus 2.94 years), because the avoided fuel cost from heat recovery accrues from the first month of operation rather than being phased in gradually, and because the combined measures reduce exposure to future tariff escalation more effectively than either technology in isolation. The levelized cost of saved energy for the integrated package, at 27.3 USD/MWh, remains substantially below the prevailing industrial electricity tariff, confirming that the additional capital is being allocated to genuinely cost-effective conservation rather than to diminishing-return measures. Sensitivity analysis indicates that the ranking of the integrated approach over the standard approach is preserved across the full tested range of discount rates and tariff escalation scenarios, and is reversed only when capital cost overrun exceeds approximately 35% combined with a discount rate above 18%, a combination judged unlikely under the enterprise's current financing terms. This robustness suggests that the EE-LCSE ranking criterion, rather than simple payback, provides a more reliable basis for prioritizing energy-efficiency investment under realistic industrial operating conditions.

4. Conclusion

This research demonstrates that the technical and economic performance of energy-efficient technology adoption in industrial enterprises depends as much on the sequencing and evaluation methodology applied as on the underlying hardware itself. By replacing simple payback with a levelized-cost-of-saved-energy ranking and by explicitly accounting for interaction effects between sequential retrofit measures, the proposed EE-LCSE framework identified an investment package that simultaneously reduces specific energy consumption by over 30%, lowers the levelized cost of conserved energy below the prevailing tariff, and nearly triples ten-year net present value relative to the sector's conventional single-measure practice, without extending the payback horizon. The practical significance of these findings is that plant-level energy managers and policy designers can apply the same decision architecture — technical audit, interaction-aware measure sequencing, and LCSE-based ranking — to other energy-intensive production lines without requiring sector-specific recalibration of the underlying method. Future extensions of this work should incorporate stochastic tariff and production-volume scenarios, extend the technology set to on-site renewable generation and thermal storage, and validate the framework through multi-site field implementation to establish its generalizability beyond the single production line examined here.

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