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# Energy Efficiency Improvement Challenges and Solutions in Beverage Production Systems

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**Abstract**

Energy efficiency has become a critical requirement for the sustainable operation of industrial production systems, particularly in energy-intensive sectors such as beverage manufacturing. This paper analyzes the energy consumption structure of beverage production systems and examines the main technological stages, including raw material preparation, thermal treatment, cooling, filling, and packaging, in order to determine their electrical and thermal energy demands. The study identifies key challenges affecting energy efficiency, including obsolete equipment, inefficient process design, poor operational practices, insufficient monitoring, and the absence of systematic energy management approaches. To address these issues, integrated technical and organizational solutions are proposed. These include equipment modernization with high-efficiency motors and variable frequency drives, process optimization, waste heat recovery, and the implementation of energy management systems. In addition, mathematical models are developed to quantify total and specific energy consumption, evaluate equipment efficiency, and formulate single- and multi-criteria optimization problems aimed at minimizing energy use, operational costs, and environmental impact. The proposed system-level optimization approach enables coordinated control of interconnected processes and improves overall production performance. The results demonstrate that comprehensive energy efficiency strategies can significantly reduce energy consumption, lower operating costs, and decrease greenhouse gas emissions, thereby contributing to the development of sustainable, reliable, and economically efficient beverage production systems.

**Keywords:** energy efficiency, beverage production systems, industrial energy optimization, energy management, sustainability.

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# İçki istehsalı sistemlərində enerji səmərəliliyinin artırılması problemləri və həlli yolları

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**Xülasə**

Enerji səmərəliliyi, xüsusilə içki istehsalı kimi enerji tutumlu sahələrdə sənaye istehsal sistemlərinin dayanıqlı fəaliyyətinin təmin edilməsində əsas amillərdən birinə çevrilmişdir. Bu məqalədə içki istehsalı sistemlərində enerji istehlakının strukturu təhlil olunur, xammalın hazırlanması, qarışdırma, istilik emalı, soyutma, doldurma və qablaşdırma mərhələləri üzrə istilik və elektrik enerjisinə olan tələbat qiymətləndirilir. Enerji səmərəliliyinə mənfi təsir göstərən əsas problemlər, o cümlədən köhnəlmiş avadanlıqların istifadəsi, qeyri-optimal proses layihələndirilməsi, səmərəsiz istismar rejimləri, monitorinq və məlumat çatışmazlığı, eləcə də sistemli enerji idarəetməsinin olmaması müəyyən edilmişdir. Bu problemlərin aradan qaldırılması məqsədilə texniki və təşkilati xarakterli inteqrasiya olunmuş həllər təklif edilir. Yüksək səmərəli mühərriklərin və tezlik çeviricilərinin tətbiqi ilə avadanlıqların modernləşdirilməsi, proseslərin optimallaşdırılması, tullantı istiliyin bərpası və enerji idarəetmə sistemlərinin tətbiqi əsas istiqamətlər kimi göstərilir. Eyni zamanda, ümumi və xüsusi enerji sərfiyyatının qiymətləndirilməsi, avadanlıqların faydalı iş əmsalının müəyyən edilməsi, enerji, xərc və ekoloji təsirin minimumlaşdırılması üçün tək və çoxmeyarlı optimallaşdırma modelləri hazırlanmışdır. Sistem səviyyəsində inteqrasiya olunmuş optimallaşdırma yanaşması istehsal proseslərinin əlaqələndirilmiş idarə olunmasına imkan verir və ümumi enerji göstəricilərini yaxşılaşdırır. Tədqiqatın nəticələri göstərir ki, kompleks enerji səmərəliliyi strategiyalarının tətbiqi enerji istehlakını və istismar xərclərini əhəmiyyətli dərəcədə azaldır, istixana qazı emissiyalarını minimumlaşdırır və dayanıqlı, etibarlı və iqtisadi cəhətdən səmərəli içki istehsalı sistemlərinin formalaşdırılmasına töhfə verir.

**Açar sözlər:** enerji səmərəliliyi, içki istehsalı sistemləri, sənaye enerji optimallaşdırılması, enerji idarəetməsi, dayanıqlılıq.

# Проблемы повышения энергоэффективности в системах производства напитков и пути их решения

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**Аннотация**

Энергоэффективность является одним из ключевых факторов обеспечения устойчивого функционирования промышленных производственных систем, особенно в энергоёмких отраслях, таких как производство напитков. В данной статье анализируется структура энергопотребления систем производства напитков, а также оцениваются потребности в тепловой и электрической энергии на основных технологических этапах, включая подготовку сырья, смешивание, тепловую обработку, охлаждение, розлив и упаковку. Определены основные проблемы, снижающие энергоэффективность, среди которых использование устаревшего оборудования, нерациональное проектирование процессов, неэффективные режимы эксплуатации, недостаточный мониторинг и отсутствие системного энергетического менеджмента. Для решения выявленных проблем предложены интегрированные технические и организационные меры, включающие модернизацию оборудования с применением высокоэффективных электродвигателей и частотных преобразователей, оптимизацию технологических процессов, рекуперацию отходящего тепла и внедрение систем энергетического менеджмента. Разработаны математические модели для количественной оценки общего и удельного энергопотребления, определения эффективности оборудования, а также формулирования одно- и многокритериальных задач оптимизации, направленных на минимизацию энергозатрат, эксплуатационных расходов и экологического воздействия. Интегрированный системный подход к оптимизации обеспечивает согласованное управление взаимосвязанными процессами и повышение общей энергетической эффективности производства. Полученные результаты показывают, что реализация комплексных стратегий энергоэффективности позволяет существенно сократить энергопотребление, снизить затраты и выбросы парниковых газов, способствуя созданию устойчивых, надёжных и экономически эффективных систем производства напитков.

**Ключевые слова:** энергоэффективность, системы производства напитков, промышленная оптимизация энергопотребления, энергетический менеджмент, устойчивое развитие.

## Introduction

The beverage industry represents a major segment of the global food processing sector and plays a significant role in economic development, employment, and consumer supply. Beverage production systems operate under strict quality, hygiene, and safety requirements, which results in high energy demand across different production stages and makes energy consumption one of the most critical operational challenges for manufacturers [1].

In recent decades, energy prices have increased steadily, while environmental regulations have become more stringent. As a result, energy efficiency improvement has become not only an economic necessity but also an environmental and regulatory obligation for industrial enterprises [2,3].

Despite the availability of modern energy-efficient technologies, many beverage production facilities continue to operate with outdated equipment and inefficient energy management practices. Therefore, a comprehensive analysis of energy efficiency challenges and the development of integrated solutions is essential for sustainable industrial operation [4].

## The aim of the work

This paper aims to analyze the energy consumption structure of beverage production systems, identify key challenges affecting energy efficiency, and propose practical solutions based on technological, organizational, and system-level approaches.

## Problem statement

Beverage production systems consist of multiple interconnected technological processes that transform raw materials into finished products. Although production lines vary depending on product type, common stages include raw material preparation, mixing, thermal treatment, cooling, filling, and packaging [5].

Thermal energy is mainly used in heating, pasteurization, sterilization, and cleaning-in-place processes, while electrical energy powers motors, pumps, compressors, conveyors, and automation systems. The interaction between these processes determines the overall energy performance of the production system [6].

Production facilities often operate under variable loads due to changes in production volume, product diversity, and seasonal demand. This variability complicates energy management and increases the risk of inefficiencies if systems are not properly optimized.

Energy consumption in beverage production systems consists of several major components, including thermal, electrical, refrigeration, and auxiliary energy uses. Thermal processes account for a significant share of the total energy demand, as operations such as heating, pasteurization, sterilization, and cleaning require substantial amounts of thermal energy. Inefficient heat transfer mechanisms, excessive safety margins, and the absence of heat recovery systems frequently result in considerable energy losses and reduced overall efficiency [7].

In addition to thermal requirements, electrical energy is extensively consumed by motors, pumps, compressors, refrigeration units, and packaging equipment. Among these, electric motors represent the dominant share and may account for more than half of the total electricity consumption in beverage production facilities. The performance and efficiency of these motors largely depend on their design characteristics, operating conditions, and applied control strategies [8].

Cooling and refrigeration systems constitute another highly energy-intensive part of beverage production due to their essential role in preserving product quality and ensuring process stability. However, inadequate system design, insufficient maintenance practices, and improper control methods can significantly increase energy consumption and reduce operational efficiency [9].

Furthermore, auxiliary systems such as compressed air generation, lighting, ventilation, and water treatment contribute noticeably to the overall energy demand. Although the energy consumption of each auxiliary subsystem may appear relatively small, their cumulative effect can be substantial when not properly monitored and managed [10].

**Challenges Affecting Energy Efficiency**

**Technological Challenges.** The use of obsolete and inefficient equipment remains one of the main barriers to energy efficiency improvement. Old motors, compressors, and heat exchangers often operate below modern efficiency standards. In addition, limited automation and outdated control systems prevent real-time optimization of energy consumption [11].

**Process Design and Operation Challenges.** Improper process design leads to excessive energy use through unnecessary heating, cooling, and material handling. Long idle times, poor synchronization between processes, and frequent start-stop operations further reduce energy efficiency. These problems are often caused by insufficient system-level analysis and lack of optimization [12].

**Organizational and Management Challenges.** Energy efficiency is frequently treated as a technical issue rather than a strategic management priority. Many enterprises lack formal energy management systems, defined performance indicators, and trained personnel responsible for energy efficiency. As a result, many cost-effective energy-saving opportunities remain unexploited [13].

**Data and Monitoring Challenges.** Accurate data collection and analysis are essential for effective energy management. However, many beverage production facilities lack comprehensive monitoring systems capable of providing real-time information on energy consumption. Without reliable data, identifying inefficiencies and evaluating improvement measures becomes difficult [14].

**Problem solution**

The article presents solutions for improving energy efficiency in beverage production systems through technical, organizational, and system-level approaches. Equipment modernization, process optimization, waste energy recovery, mathematical modeling, and the implementation of energy management systems are proposed as effective measures to reduce energy consumption. The economic and environmental benefits of the suggested approaches are highlighted, and future research directions are identified.

**Equipment Modernization.** Replacing outdated equipment with energy-efficient alternatives is one of the most effective ways to reduce energy consumption. High-efficiency motors, compressors, and heat exchangers significantly improve system performance. Variable frequency drives allow equipment to operate according to actual load requirements, thereby reducing unnecessary energy use [15].

**Process Optimization.** Process optimization involves analyzing and adjusting operating parameters to minimize energy consumption while maintaining product quality. Measures such as reducing excessive heating, optimizing cooling temperatures, and minimizing idle times can lead to substantial energy savings without major capital investment [16].

**Waste Energy Recovery.** Waste energy recovery systems capture and reuse energy that would otherwise be lost. In beverage production systems, waste heat from thermal processes can be used for preheating raw materials or process water. Integrating waste energy recovery improves overall system efficiency and reduces fuel consumption [17].

**Mathematical Formulation of Energy Efficiency Improvement**

Energy efficiency improvement in beverage production systems can be quantitatively evaluated using mathematical models that describe energy consumption, production output, and system constraints.

Total energy consumption can be expressed as the sum of electrical and thermal energy consumption across all production stages [18].

$$E_{total} = \sum_{i=1}^{n} \left(E_{el,i} + E_{th,i}\right)$$

where $E_{total}$– total energy consumption of the production system (kWh); $E_{el,i}$ – electrical energy consumption of process $i$(kWh); $E_{th,i}$ – thermal energy consumption of process $i$(kWh); $n$– number of technological processes.

Specific energy consumption is used as a key indicator to evaluate energy efficiency per unit of production, where a reduction indicates improved performance.

$$SEC = \frac{E_{total}}{Q}$$

where: $SEC$– specific energy consumption (kWh/hl or kWh/unit); $Q$– total production output.

A reduction in $SEC$indicates improved energy efficiency.

The efficiency of individual equipment can be defined as the ratio of useful output power to input power:

$$\eta_i = \frac{P_{out,i}}{P_{in,i}}$$

where $\eta_i$– efficiency of equipment $i$; $P_{out,i}$– useful output power (kW); $P_{in,i}$– input power (kW).

For system-level analysis, weighted average efficiency values can be applied:

$$\eta_{sys} = \frac{\sum_{i=1}^{n} P_{out,i}}{\sum_{i=1}^{n} P_{in,i}}$$

The main objective of energy optimization is minimizing total energy consumption while satisfying production requirements:

$$\min \; E_{total} = \sum_{i=1}^{n} \left(E_{el,i} + E_{th,i}\right)$$

subject to the following constraints:

$$Q \geq Q_{min}$$
$$P_i^{min} \leq P_i \leq P_i^{max}$$
$$\eta_i \geq \eta_i^{min}$$

where $Q_{min}$– minimum required production output; $P_i$ – operating power of equipment $i$; $\eta_i^{min}$– minimum acceptable efficiency.

Recovered waste energy can be calculated as:

$$E_{rec} = \alpha \cdot E_{loss}$$

where $E_{rec}$ – recovered energy (kWh); $E_{loss}$ – total waste energy available (kWh); $\alpha$ – recovery coefficient ( $0 < \alpha < 1$ ).

The effective energy consumption after

recovery becomes:

$$E_{eff} = E_{total} - E_{rec}$$

Energy cost minimization can be formulated as:

$$\min\ C = \sum_{j=1}^{m} E_j \cdot c_j$$

where $C$– total energy cost; $E_j$– energy consumed from source $j$; $c_j$– unit cost of energy source $j$; $m$ – number of energy sources.

Multi-criteria optimization models enable balancing energy efficiency, economic cost, and environmental impact, providing a comprehensive framework for sustainable industrial operation [19]:

$$\min\ F = w_1 E_{total} + w_2 C + w_3 CO_2$$

where $F$– composite objective function; $CO_2$ – greenhouse gas emissions; $w_1, w_2, w_3$– weighting coefficients.

**Energy Management Systems**

The implementation of energy management systems enables continuous monitoring, analysis, and improvement of energy performance. Such systems provide a structured framework for identifying inefficiencies, setting improvement targets, and tracking progress over time.

Integrated system-level optimization considers interactions between processes and enables coordinated control strategies. This approach provides greater benefits than isolated improvements and supports long-term sustainability.

**Environmental and Economic Benefits**

Improving energy efficiency in beverage production systems results in multiple benefits. Reduced energy consumption lowers operational costs and increases profitability. At the same time, decreased greenhouse gas emissions contribute to environmental protection and regulatory compliance. Energy efficiency improvement also enhances system reliability and extends equipment lifespan.

## Conclusion

Improving energy efficiency in beverage production systems is a complex yet essential task driven by economic, environmental, and regulatory requirements. The conducted analysis shows that high energy consumption in these systems is mainly associated with thermal processes, electric motors, refrigeration units, and auxiliary systems, while existing technological and organizational shortcomings further increase energy losses. This study has identified the key challenges affecting energy performance and proposed integrated technical and managerial solutions to address them [20].

Measures such as equipment modernization, process optimization, waste energy recovery, mathematical modeling, and the implementation of energy management systems enable significant reductions in energy consumption, lower operational costs, and reduced environmental impact. System-level optimization approaches ensure better coordination among production processes and support sustainable industrial development.

Future research should focus on the application of advanced optimization methods, digitalization, and the integration of renewable energy sources, as well as the use of artificial intelligence and data analytics to further enhance energy efficiency and overall system performance.

## Conflict of Interests

The author declares there is no conflict of interests related to the publication of this article.

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