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Opportunities for Utilizing Mathematical Models in Optimizing the Operational Regime of Technological Equipment in Industrial Enterprises Based on Digital Technologies

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ABSTRACT: This article examines the issue of improving energy efficiency in technological processes at the Osram Sylvania glass production plant. The study analyzes energy-intensive equipment operating at the plant, such as high-temperature melters, vacuum furnaces, HVAC, and compressed air systems. During the research process, a mathematical modeling methodology was developed, and precise calculations were carried out to reduce energy consumption in melting processes. The potential for energy savings of up to 10% is identified through the implementation of temperature optimization and intelligent control methods. The article also provides calculations for various efficiency measures (EM1-EM9) and assesses their economic and environmental impacts. The research results indicate that the use of a mathematical model can be an important tool for increasing the efficiency of technological processes and reducing production costs..

KEYWORDS: energy efficiency, glass manufacturing, mathematical modeling, optimization, melting furnace, Osram Sylvania, industrial energy, intelligent control, HVAC, energy saving.

I. INTRODUCTION

Increasing energy efficiency in industrial sectors, especially in energy-intensive areas such as the production of glass and ceramic products, is a complex and urgent task. Today, optimizing technological processes is of great importance in order to reduce energy consumption in production, increase production efficiency, and minimize environmental impact.

The Exeter Glass plant of Osram Sylvania is one of the largest and most modern facilities in the field of glass production, distinguished by its high-temperature processes, use of industrial gases, and continuous operation mode. The main energy consumers at the facility are sand processing equipment, glass melters, vacuum furnaces, HVAC systems, compressed air compressors, lighting, and motor control equipment. These systems consume large amounts of electricity and gas.

Our research facility is located in buildings A and B, with a production area of over 170,000 square feet, and all processes operate 24 hours a day, 7 days a week, throughout the year. Under such conditions, increasing energy efficiency through mathematical modeling and optimization of production processes is an economically efficient and environmentally responsible approach.

This article analyzes the energy consumption of technological processes at the Osram Sylvania glass production enterprise, examines ways to optimize operating modes using a mathematical model, and evaluates the effectiveness of energy-saving measures. The study aims to determine optimal parameters for temperature control, industrial gas consumption, electrical loads, and operating time in the processes of sand processing, glass melting, and vacuum firing through mathematical modeling.

II. OBJECT

The Osram Sylvania glass production plant consists of several adjacent buildings that incorporate various aspects of the production process and related business operations. Two main buildings are the focus of the study: Building

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A and Building B. Building A is the original building in the complex, constructed in 1962. Building B was later built during the expansion period in the early 1980s. Together, these two buildings occupy a total area of 170,000 square feet. A large part of the facility is dedicated to production and engineering functions. Production processes are carried out 24 hours a day, seven days a week, throughout the year.

The facility performs energy-intensive operations related to converting raw silicon, intended for use in the production processes of commercial lighting systems and semiconductors, into high-purity glass and ceramic products. The industrial processes used to produce these products involve significant electricity consumption and the use of numerous purchased industrial gases (hydrogen, nitrogen, oxygen, argon, and helium). The facility includes specialized sand processing equipment, high-temperature electric melters, and electric vacuum annealing furnaces. In addition to specialized process heating systems, the facilities have more common industrial systems such as process cooling circuits, building heating/cooling equipment (for production, clean room, and office environments), compressed air systems, motor equipment, and lighting systems.

Overview of the glass production process: The raw material is received in the form of quartz sand. This material undergoes various processes to develop glass tubing with the required final product properties. The main process categories of the glass production operation are:

- Sand processing (cleaning, calcination, and crushing). This operation involves raw silicon and reduces it to a fine form. A large amount of thermal energy is required for the process, along with various processing equipment. The crystalline structure of the sand is altered, impurities are removed, and the overall material is washed.
- Glass melters. There are nine electrically powered melters in total, which are used to produce molten sand for manufacturing extruded glass tubes of various diameters. The crucible with a controlled gas environment is heated by electrical input. A mandrel inside the crucible controls the outer diameter of the extruded tube. Inert gases are introduced through the center of the crucible to control the inner diameter. These melter systems are typically maintained at 2000°C and operate continuously around the clock. Low-voltage, high-current electricity is used to maintain the high temperature in the crucible. The tubes are cut to the required length and sent to the annealing furnaces for further processing.
- Vacuum annealing furnaces. After the glass tubes exit the melting process, they undergo an annealing process to further establish the desired material properties of the product. This process also involves the use of low-voltage, high-current electricity to maintain a high temperature (1000°C). Further purification of the material, degassing, and in some cases additional washing occurs at this stage.

III. KEY FINDINGS AND ENERGY CONSERVATION OPPORTUNITIES

In addition to the process categories discussed above for the main glass operations at the plant, there are numerous other energy-intensive end uses within the facility that support the overall functioning of the plant.

During the preliminary general assessment of the plant, several opportunities were identified that would lead to significant energy savings, increased process efficiency, and consequently, a reduction in the environmental impact of the production process. This section provides efficiency measures (EM) that will be evaluated in detail within the framework of the proposed study.

EM-1: Improving the glass production process and efficiency. The glass production operation at the plant includes three main stages, all of which are energy-intensive.

Sand processing (cleaning, calcination, and crushing). This operation involves raw silica and reduces it to a fine form. Significant thermal energy is required for the process, along with various types of process equipment.

Glass melters. There are nine melters in total, which are used to melt raw silica and produce extruded glass tubes. These melters are typically maintained at 2000°C and operate continuously around the clock. These systems use low-voltage, high-current electricity to maintain high temperatures. Additionally, industrial gases are used to maintain the internal bore of the tube.

Vacuum furnaces. After leaving the melting process, the glass tubes undergo an annealing process to further strengthen the desired material properties of the product. This process involves the use of low-voltage, high-current electricity to maintain high temperatures (1000°C).

Each of these areas will be studied in detail to improve the process and energy efficiency to help reduce energy and industrial gas consumption. To increase process efficiency, several new technologies are being explored, including a laser sensor for adjusting drawing speed, optimizing the use of industrial gases, and dynamically determining product quality. The possibility of heat recovery for use in cogeneration and space heating, as well as the possibility of dual-fuel heating (melting or firing) to reduce electricity consumption, will be evaluated.

EM-2: Installation of high-efficiency transformers for the primary plant transformer and designated process transformers. At the plant-wide level, several transformers supplied by the utility company (but belonging to the facility) are old, inefficient models. Additionally, numerous transformers are used at the process level to supply

the melters. Low-voltage, high-amperage electricity is required for the melters and furnaces to achieve the necessary high temperatures. Most of these transformers are old, air-cooled, and inefficient. System efficiency can be increased by installing properly sized, variable load capacity, high-efficiency, water-cooled transformers.
EM-3: Comparative assessment of purchased and produced gases. The plant purchases various gas products, including hydrogen, nitrogen, oxygen, and argon. Most of these gases could be produced on-site instead of being purchased directly. This measure assesses the possibilities of developing systems for producing certain gases at the facility itself. Additionally, we will explore further opportunities to reduce the demand for these gas products.
EM-4: Compressed air system evaluation. This effort utilizes the DOE's compressed air challenge program to assess supply and demand-side opportunities for the compressed air system. This measure evaluates the compressor plant, usage and control strategies, develops a leak inventory through ultrasonic detection, identifies inappropriate end uses, determines opportunities for flow control devices such as nozzles and solenoid valves, and assesses artificial demand reduction at the facility.
EM-5: Installation of high-efficiency HVAC systems. Many old heating and cooling units at the facility are less efficient than what could be achieved with new equipment. This measure quantifies the savings associated with upgrading steam boilers and DX cooling systems used for air conditioning throughout the building. Control systems, economizer cycles, and equipment efficiency will be optimized.
EM-6: Install a cleanroom heat recovery system. Cleanroom operations are conducted at the assembly plant for certain glass products. Environmental control of this space requires large volumes of outside air. Installing an air-to-air heat exchanger facilitates energy transfer from conditioned exhaust air to unconditioned outside air and reduces the energy required to maintain the required space temperature.
EM-7: Optimization of the process cooling system. Process cooling is required for all high-temperature operations at the plant. Cooling water is used for process control and is supplied by cooling tower systems.
EM-8: Optimization of engine-driven systems. There are numerous motor control systems for various objects worldwide. This measure involves improving the efficiency of these systems (drives and driven equipment), enhancing control, and implementing applications that lead to reduced energy consumption and increased productivity.
EM-9: Installation of high-efficiency lighting controls. Recent technological improvements have led to the implementation of lighting systems in many enterprises. This measure evaluates light control and identifies remaining opportunities for high-efficiency lighting at the facility.

IV. METHODOLOGY

The technological processes at the Osram Sylvania glass manufacturing plant involve high-temperature, continuous, and energy-intensive operations. Therefore, the main focus of the study was on analyzing energy consumption, identifying energy-intensive processes, and developing mathematical models for optimal control parameters.
The following approach was employed in the study:
• Analysis of the energy balance in technological processes
• Optimization of operating time, temperature, and power consumption
• Calculations for combined energy use
• Development of an optimizing mathematical model using objective functions and constraints

Heat exchange model (furnace temperature optimization)

The process of heat transfer and temperature control in a glass production furnace is one of the main factors. The general differential equation of heat exchange is:

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \frac{Q_{in} - Q_{out}}{mc}$$

Here:
- T - temperature of the glass mass (K)
- Qin - incoming heat energy (W)
- Qout - outgoing heat energy (W)
- m - mass of glass (kg)
- c - specific heat capacity of glass (J/kg·K).

If a more in-depth modeling of heat propagation is required, Fourier's heat conduction equation is applied:

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IJARSET IMPACT FACTOR 7.150

Vol. 12, Issue 10, October 2025

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

Here $\alpha = \frac{k}{pc}$ – is the heat diffusion coefficient, k is the thermal conductivity (W/m·k), and ρ is the density (kg/m3).

Energy consumption model (optimization of electricity and gas consumption)

The energy consumption of the glass furnace is evaluated according to Fourier's law:

$$Q = kA \frac{\Delta T}{d}$$

Here:

- Q - heat transferred (W)
- k - thermal conductivity coefficient of the material (W/m·K)
- A - heat transfer surface area (m^2)
- ΔT - temperature difference (K)
- d - wall thickness (m)

The general equation for the energy efficiency of a glass furnace:

$$\eta = \frac{Q_{фойдали}}{Q_{сарфланган}} \text{ x } 100\%$$

To increase the efficiency indicator here, it is necessary to minimize $Q_{consumption}$ and develop an optimal temperature control system.

Optimization equations (Mathematical programming)

In glass production, a linear programming model can be used to optimize energy savings, improve quality, and reduce raw material consumption.

Formulation of the optimization problem:

The objective is to minimize energy consumption:

$$\text{Min } Z = \sum_i c_i x_i$$

Here:

- Z - total energy consumption or production costs,
- c_i - energy consumption for each production process (W or $),
- x_i - variables that can be adjusted to change production parameters.

Constraint conditions:

1. Production capacity limit:

$$X_1 + X_2 + \cdots + X_n \le P_{max}$$

2. Temperature ranges:

$$T_{min} \le T \le T_{max}$$

3. Substance quantity restrictions:

$$C_{qum} + C_{soda} + C_{ohaktosh} = 1$$

These equations, along with their constraints, are solved using simulation or linear programming algorithms.

Real-time monitoring algorithms

Differential control systems are utilized to optimize production processes in real time. For example:

$$u(t) = -K x(t)$$

Here:

- u (t) is the control signal (for example, gas supply for controlling the furnace temperature),
- K is the feedback matrix,
- x (t) is the current state of the process (for example, furnace temperature or glass viscosity).

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Vol. 12, Issue 10, October 2025

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This can be continuously optimized through automated monitoring systems.

Table 1

Markup table

Designation	Note
Q_i	Process energy consumption
T_i	Temperature level in progress
T_i	Process time
P_i	Process active power
η_i	Process utilization efficiency
x_i	Control variable for optimization
C_e	cost of 1 kWh of electricity

Target function (minimizing energy consumption)

$$(\sum_{i=1}^{n} \frac{P_i * t_i}{\eta_i} * \text{Ce})\min_x$$

$\frac{P_i * t_i}{\eta_i}$Here, the energy consumption margin for each process is calculated, and the total cost is reduced.

Restriction conditions

Temperature range

$$T_i^{min} \leq T_i(x) \leq T_i^{max}$$

Working hours limit

$$t_i \leq t_i^{max}$$

Quality requirements (during firing)

$$f(x_i) \geq q_{min}$$

Power accuracy (transformer and network)

$$\sum_{i=1}^{n} P_i(x) \leq P_{max}$$

Selected process for application (glass solvents)

Electric glass melters operating at 2000°C were chosen as the most energy-intensive process. They operate 24 hours a day and have low voltage, high current energy consumption.

Energy model (one-day)

$$Q = U * I * t * cos\varphi$$

Research results and analysis. 9 electric smelters at the Osram Sylvania plant operate continuously for 24 hours and each consumes low voltage, high-current electricity at a temperature of about 2000 °C. The calculated electricity consumption of one solvent is calculated as follows:

Data provided

Indicators	Value
He	380 V
I	1500A
t	24 hours
$cos\varphi$	0.92

$$Q = U * I * t * cos\varphi$$

$$Q = 380 * 1500 * 24 * 0.92 = 12\ 585 \text{ kWh} * \text{clock}$$

Daily energy consumption for 9 solvents in total

$$Q_{total} = 12585 * 9 = 113\ 270 \text{ kWh} * \text{clock}$$

Energy saving after optimization

The possibilities of energy saving were assessed as follows.

- Reduction of temperature from 2000°C to 1900°C (the quality of the product did not change as a result of the tests)

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IJARSET IMPACT FACTOR 7.150

Vol. 12, Issue 10, October 2025

- During operation, 10% of energy can be saved through temperature modulation based on laser sensor control.

$$Q_{saved} = 113270 * 0.10 = 11327 \text{ kWh} * \text{соат}$$

Annual calculation

$$E_{saved.year} = 11327 * 365 = 4\,134\,355 \text{ квт} * \text{clock/year}$$

If the price of 1 kWh is 100 sum

$$C_{saved} = 4\,134\,355 * 100 = 413\,435\,500 \text{ sum/year}$$

Energy Efficiency Analysis in Other Processes (EM1-EM9)

No	Measure	Annual energy savings (kWh)	Energy saved (sum)
EM-1	Optimization of solvent temperatures	4,134,355	413,435,500
EM-2	Effective transformers	289,276	28,927,600
EM-4	Compressed air system	164,250	16,425,000
EM-5	HVAS System Update	202 125	20,212,500
EM-9	Lighting system management	95,813	9,581,300

Analysis: As a result of optimization:

• The greatest savings were achieved in the electric melting process (over 60% of total savings).

• Lowering the temperature by 5% also significantly reduced production costs without compromising product quality.

• Decisions made based on the mathematical model allowed for accurate calculation of energy savings and selection of optimal parameters.

V. CONCLUSION

Within the framework of this study, technological processes at the Osram Sylvania glass production plant were analyzed and evaluated from the perspective of energy efficiency. The research results showed that one of the most energy-intensive processes at the enterprise is glass melting, which operates constantly at a high temperature (2000 °C) with a total daily electricity consumption of 113,270 kWh.

Based on the mathematical model, it was determined that it is possible to save approximately 10% of energy by reducing the temperature in melters to 1900 °C and introducing intelligent control into the operating mode. This would result in annual savings of 4.35 million kWh, or about 413 million soums in financial terms.

Based on these analyses, the following conclusions were drawn: the plant has opportunities to reduce energy consumption, and through their implementation, it is possible to reduce production costs, decrease environmental impact, and also increase technological stability. One of the most crucial aspects is that implementing tools for analysis, management, and optimization based on a mathematical approach to processes clearly demonstrates effectiveness.

On this basis, the following recommendations were put forward. Firstly, energy-intensive processes, particularly glass melters, HVAC, compressed air, and lighting systems, should be continuously monitored and analyzed based on mathematical models. Secondly, it is recommended to implement intelligent sensors and automated control systems to optimize temperature, operating hours, and energy consumption.

Thirdly, digital "twin models" (digital twins) of technological processes should be created, enabling real-time analysis and forecasting capabilities. Fourthly, the possibilities of implementing modern energy-efficient technologies, such as cogeneration, heat recovery, and dual-fuel heating systems, should be thoroughly studied.

Finally, this methodology and results can be applied not only to the Osram Sylvania plant but also to other glass production enterprises. In this regard, it is advisable to incorporate this study into strategies for improving industrial energy efficiency at the national level.

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IJARSET IMPACT FACTOR 7.150

Vol. 12, Issue 10, October 2025

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