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STEAM TURBINE DEPLOYMENT IN EMBEDDED POWER GENERATION SYSTEM IN ENUGU REGION, NIGERIA

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Abstract: **This study examines the technical and economic viability of integrating steam turbines into embedded power generation systems in the Enugu region of Nigeria. Faced with unstable grid supply and increasing industrial energy demands, the region presents a strong case for decentralized generation solutions. Using a combined-cycle configuration that recovers exhaust heat from gas turbines, the research models the performance of a steam turbine system designed to enhance overall efficiency and energy utilization. Mathematical models were developed to simulate energy recovery and turbine output using MATLAB/Simulink. The results show that the steam turbine contributed approximately 0.70 MW of additional power with a local efficiency of 24%, representing a significant secondary utilization of thermal energy without additional fuel input. These findings highlight the potential of cogeneration to improve operational efficiency, reduce transmission losses, and promote sustainable industrial energy supply. The study recommends targeted policy incentives, local capacity development, and streamlined regulations to facilitate the adoption of steam turbine-based embedded generation across the region.**

Keywords: **Steam Turbine, Enugu Region, Embedded Power Generation, Cogeneration, Operational Efficiency.**

I. INTRODUCTION

Nigeria's power sector faces persistent challenges, including inadequate generation capacity, unreliable grid infrastructure, and frequent outages that hinder industrial productivity and economic growth. The Enugu region, once a hub of coal-powered energy and industrial activity, now contends with erratic electricity supply that affects both urban and rural communities. As the demand for stable and efficient power continues to rise, particularly among manufacturing, agro-processing, and commercial enterprises, there is a growing need for decentralized energy solutions that bypass the limitations of the national grid. Decentralised energy system theory extends beyond technical aspects to incorporate economic, social, and environmental dimensions of distributed generation. This theory, developed through the work of (Alanne and Saari 2016), provides a comprehensive framework for evaluating the sustainability implications of transitioning from centralized to distributed energy paradigms. Embedded power generation, which involves producing electricity close to the point of consumption, offers a promising alternative. This theory incorporates concepts such as mean time between failures (MTBF), mean time to repair (MTTR), and system availability that are directly relevant to evaluating the potential reliability improvements from embedded generation systems (Billinton and Allan, 2019). Among the technologies suited for embedded generation, steam turbines stand out for their ability to deliver consistent power output, especially when integrated into cogeneration systems that simultaneously produce electricity and useful thermal energy. This dual capability makes steam turbines particularly attractive for industries with significant heat requirements, such as breweries, cement plants, and textile mills, many of which are active in the Enugu region. The steam turbine proves to be an important tool in converting thermal energy into mechanical energy. Steam produced in the HRSG enters the steam Turbine, where it expands and strikes the blades of the Turbine. This mechanical energy is then converted to electrical energy. Having the working fluid couple, the heat from the gas turbine exhaust, and the power generated by the steam turbine increases the overall efficiency of the electricity generation process (Arpit and Das, 2023). Despite their technical advantages, steam turbines are often overlooked in Nigeria's embedded generation landscape due to concerns about high capital costs, maintenance complexity, and limited local expertise. However, recent developments in modular turbine design, improved fuel efficiency, and growing interest in industrial self-generation suggest that steam turbines could play a strategic role in revitalizing Enugu's energy infrastructure. This study explores the feasibility, economic viability, and strategic benefits of deploying steam turbines in embedded power generation systems across Enugu. It assesses key cost-benefit parameters, evaluates local industrial energy needs, and identifies policy and investment pathways to support adoption. By focusing on the Enugu region, the research aims to provide actionable insights for stakeholders seeking to enhance energy security, stimulate industrial growth, and promote sustainable development through localized power solutions.

II. METHODOLOGY

A. Design Method

The study adopts a simulation-based analytical approach to evaluate the performance of steam turbines in embedded power generation. MATLAB/Simulink was used to model a combined-cycle system that integrates gas and steam turbines with a Heat Recovery Steam Generator (HRSG).

B. System Description

The model represents a two-stage energy conversion process:

Stage 1**:** A gas turbine combusts gas to generate electricity and produces exhaust gases.

Stage 2**:** The exhaust gases pass through an HRSG to generate high-pressure steam. This steam drives a turbine (ST), producing additional power through a connected generator (G2).

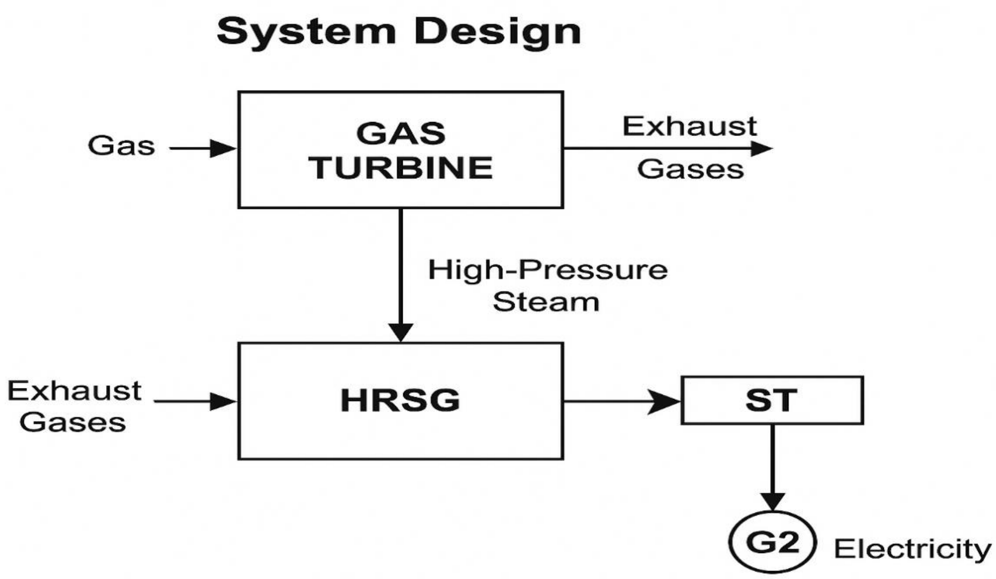

Fig.1: System Design Drawing

C. Mathematical Model for the Steam Turbine Power Generation System

The research analyzed the energy flow and recovery process in a combined cycle power generation system, specifically focusing on heat recovery from gas turbine exhaust gases to generate additional power through a steam turbine. This represents a cascaded energy recovery approach that maximizes overall system efficiency.

The analysis was conducted using a series of mathematical equations to model the energy transformation processes.

Heat Energy in Exhaust Gases (Directed to HRSG) is expressed in Equation 1 below.

$$Q_{exhaust} = Q_{input} - P_{GT} - Q_{loss} \quad (1)$$

The Equation represents the heat balance for a gas turbine system, showing how the input energy is distributed among useful work and losses. Where: $Q_{exhaust}$= The amount of heat energy carried away by the exhaust gases after the gas turbine has extracted useful work,

Q_{input}= Heat Input,

P_{GT} = Gas Turbine Output

Q_{loss} = Heat Losses Heat Recovery in HRSG is Expressed in Equation 2 below.

$$Q_{HRSG} = \dot{m_g} \cdot c_p \cdot (T_{exhaust} - T_{stack}) \quad (2)$$

The Equation represents the heat energy recovered by a Heat Recovery Steam Generator (HRSG) in a combined cycle power plant. Where: Q_{HRSG} = Heat Recovered by the HRSG,

$\dot{m_g}$= Mass Flow Rate of Exhaust Gases

c_p = Specific Heat Capacity of the Exhaust Gases,

$T_{exhaust}$ = Exhaust Gas Temperature

T_{stack} = Stack Gas Temperature.

The power output of the steam turbine can be expressed as in Equation 3 below.

$$P_{ST} = \dot{m_s} \cdot (h_1 - h_2) \quad (3)$$

Where: P_{ST} = Steam Turbine Power Output

$\dot{m_s}$ = Mass Flow Rate of Steam

h_1 = Enthalpy of Steam at Turbine Inlet

h_2 = Enthalpy of Steam at Turbine Exit

Electricity Generation by Generator G2 expressed as in Equation 4 below.

$$P_{G2} = P_{ST} \cdot \eta_{G2} \quad (4)$$

Where:

P_{G2}: Electrical power generated by Generator G2 (W)

η_{G2}: Efficiency of Generator G2

Heat Recovery in Second HRSG expressed as in Equation 5 below.

$$Q_{HRSG2} = \dot{m_g} \cdot c_p \cdot (T_{HRSG1,out} - T_{HRSG1,stack}) \quad (5)$$

Where:

Q_{HRSG2} = Heat Recovered by the Second HRSG Stage

$\dot{m_g}$ = Mass Flow Rate of Exhaust Gases

c_p = Specific Heat Capacity of the Exhaust Gases

$T_{HRSG1,out}$ = Exhaust Gas Temperature Leaving HRSG1

$T_{HRSG1,stack}$ = Exhaust Gas Temperature Leaving HRSG1 to HRSG2 or Stack.

D. Steam Turbine Model

Figure 2 below provides a clear and comprehensive general vision of what a steam turbine system looks like, and how the steam and energy move through the system and its various parts. The foundation of this system is the Steam Boiler, which is responsible for heating water to create high-pressure steam. This steam is well-regulated to generate an appropriate pressure and temperature that positively impacts the efficiency of other downstream processes. The Throttle Valve is required to control the flow of high-pressure steam to the HPT while controlling the position dynamically in response to power requirements. Thus, it is an essential component of the modern power plant.

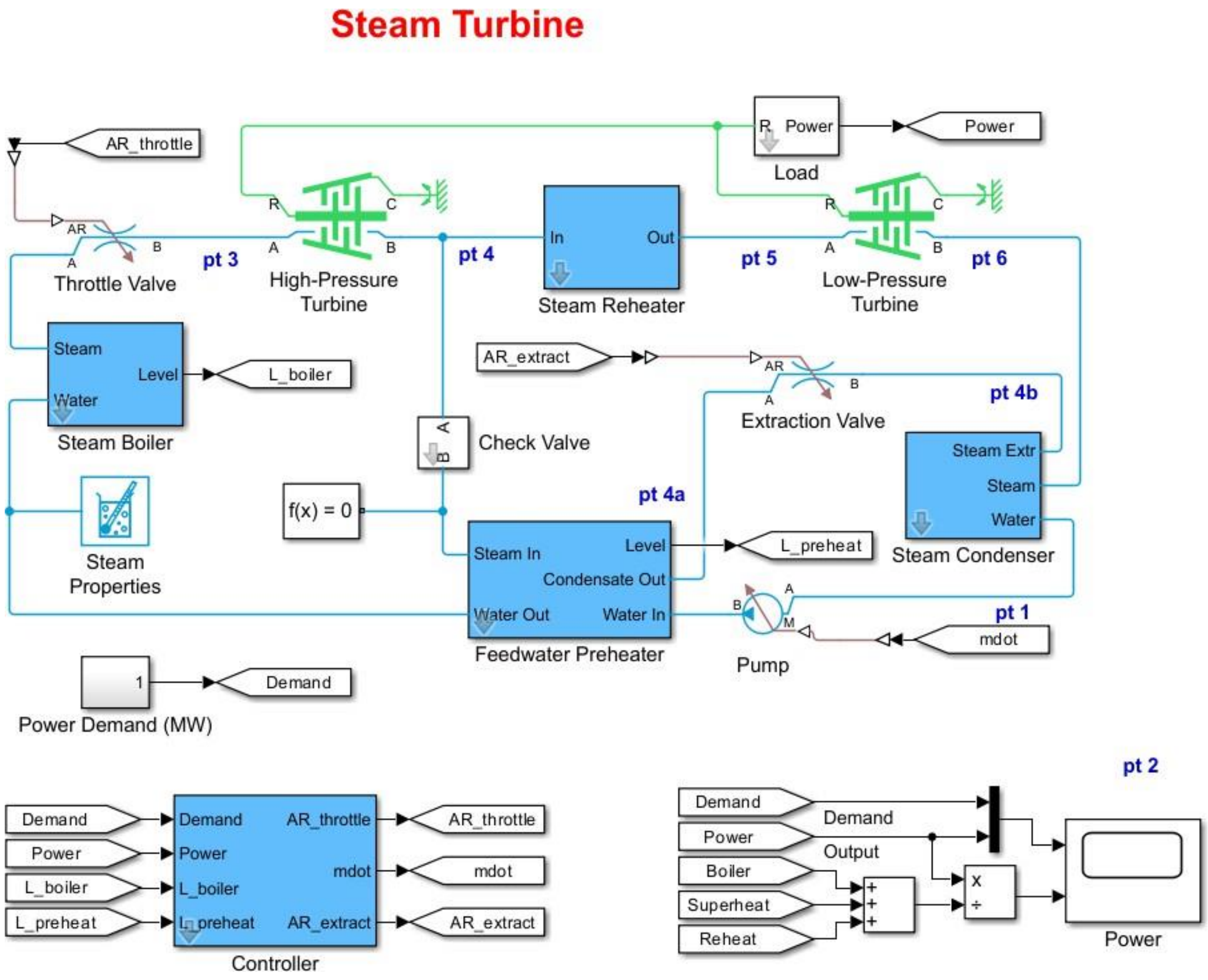

Fig.2: MATLAB/SIMULINK Model of the Steam Turbine Power Generation Design

E. Simulation Setup

Input parameters such as exhaust gas temperature, pressure ratios, steam flow rate, and turbine efficiency were selected based on industry-standard values and adapted to the operational conditions typical of Enugu's industrial energy profile.

F. Performance Indicators

Two main metrics were analyzed:

Steam turbine electrical output (MW)

Global efficiency (%)**,** defined as total useful energy output divided by total fuel energy input at the gas turbine.

G. Validation

Results from the simulation were benchmarked against theoretical expectations from combined-cycle literature (Ahmadi et al., 2023; Raptis et al., 2020) to confirm thermodynamic consistency.

III. RESULTS AND DISCUSSION

Performance Analysis of Steam Turbine Electrical Power and Global Efficiency.

This section provides a focused evaluation of the steam turbine's electrical power generation and its global efficiency within the integrated hybrid turbine system. As simulated in the implemented model, the steam turbine contributes a net electrical output of 0.70 MW, extracted exclusively from the thermal energy harnessed downstream of the gas turbine. This electrical output represents the direct transformation of steam's enthalpic potential recovered from the gas turbine exhaust into mechanical and subsequently electrical energy.

Global efficiency, in this context, extends beyond the component's individual thermal performance and examines the contribution of the steam turbine in relation to the total energy flow initiated by the primary fuel input to the system. While the local efficiency of the steam turbine was computed at 0.24 (24%), its global efficiency reflects how effectively the gas turbine's waste heat is repurposed. When considered relative to the total fuel energy input at the gas turbine stage, the steam turbine's performance reveals a highly favourable secondary utilization of energy that would otherwise be lost in conventional setups.

The simulation validates that the steam turbine does not incur any additional fuel cost, thus making its output highly economical and environmentally advantageous. This aligns with cogeneration principles, where cascading thermodynamic cycles maximize energy extraction per unit of primary input.

In essence, the steam turbine demonstrates high electrical output in converting thermal energy and strong global efficiency as a secondary unit in the energy chain. Its ability to contribute significantly to total system output without increasing the system's fuel burden affirms its strategic role in achieving both operational efficiency and sustainable energy delivery within the proposed embedded power generation architecture.

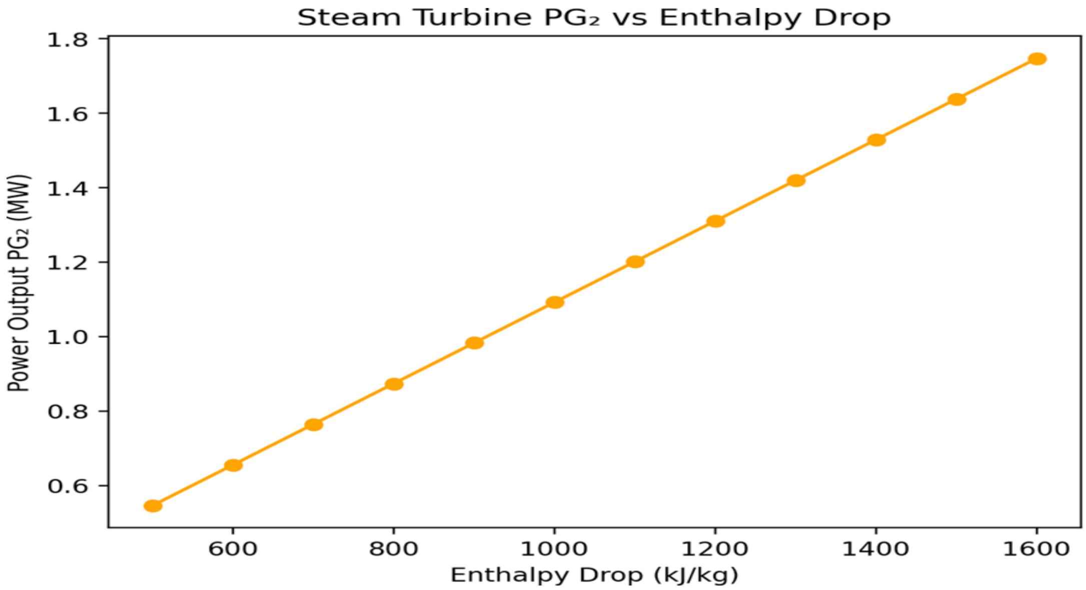

Fig.3: Steam Turbine Enthalpy PG2 vs Enthalpy Drop

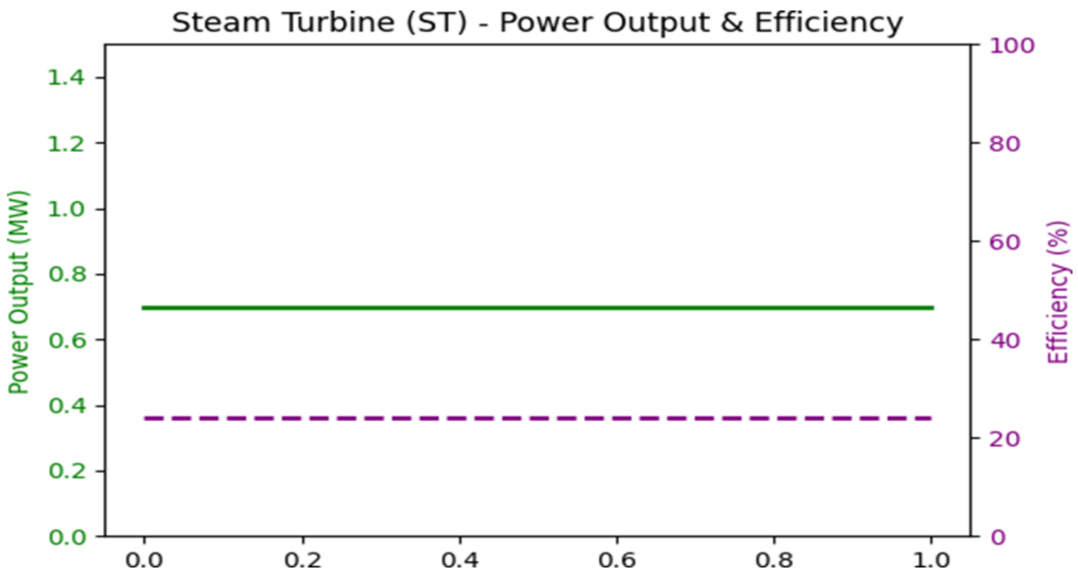

Fig.4: Steam Turbine – Power out and Efficiency

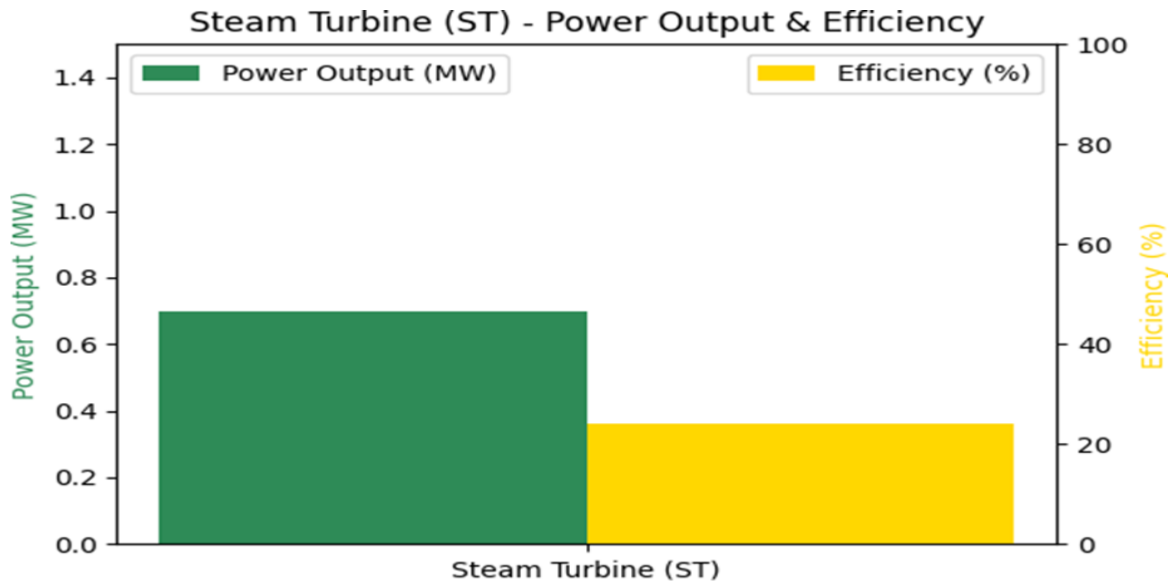

Fig. 5: Steam Turbine Electrical Power and Global Efficiency Bar Chart

Figure 3 illustrates the performance metrics of the steam turbine (ST) within the integrated turbine system. The simulation revealed that the steam turbine generated a power output of 0.70 MW, which was extracted from the thermal energy recovered via the heat recovery steam generator (HRSG) positioned downstream of the gas turbine. This setup captures the exhaust heat from the gas turbine, converting otherwise wasted thermal energy into useful mechanical work.

The corresponding efficiency achieved by the steam turbine reflects the optimized use of the enthalpy drop across turbine stages. Unlike gas turbines that depend on direct fuel combustion, the steam turbine relies on the enthalpic energy of superheated steam. The efficiency here is computed as the ratio of power output to the energy made available from the input steam enthalpy.

Such an efficiency is indicative of minimal irreversibility and effective expansion of steam within the turbine stages. This is especially commendable given the intermediate nature of the steam turbine in the cascade of energy conversion, receiving energy secondarily from the gas turbine's exhaust.

Furthermore, this performance underscores the value of incorporating a cogeneration strategy in industrial environments. By harnessing residual energy from the gas turbine, the steam turbine enhances total system output without additional fuel input, thus improving overall thermal utilization and supporting cleaner, more economical power generation.

In summary, Figure 4 confirms the steam turbine’s role as an effective secondary converter that significantly boosts the system’s total output while maintaining excellent thermodynamic efficiency. This reinforces the practical viability of heat recovery integration in embedded power generation for regional supply stabilization.

IV. CONCLUSION

The deployment of steam turbines in embedded power generation systems presents a strategic opportunity to address the persistent energy challenges facing the Enugu region. With its growing industrial base and unreliable grid supply, Enugu stands to benefit significantly from decentralized power solutions that offer both reliability and efficiency. Steam turbines, particularly in cogeneration configurations, can optimize fuel use, reduce transmission losses, and enhance industrial productivity making them well-suited for the region’s energy-intensive sectors.

This study’s cost-benefit analysis reveals that while steam turbines require substantial initial investment, their long-term economic and operational advantages outweigh those of conventional alternatives. The potential for integrating locally available fuels, such as biomass and natural gas, further strengthens the case for regional adoption. To unlock these benefits, targeted policy support, technical capacity building, and streamlined regulatory frameworks are essential.

The study concludes that steam turbines represent a viable enhancement to embedded power generation in Enugu’s industrial sector. By leveraging waste heat from gas turbines, they provide an additional energy source that increases total system output without increasing fuel consumption. Though the initial capital cost may be significant, the long-term benefits reduced energy losses, operational cost savings, and improved power reliability justify investment.

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