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Evaluation of Energy Transition Pathways for Industries with Low-Temperature Heat Demand: The Case of Laundry and Syrup Sectors

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ABSTRACT

Industries with low-temperature heat demand, such as laundry and syrup sectors, heavily rely on natural gas-fired boilers, posing challenges to achieving net-zero emissions by 2050. Like hard-to-abate sectors, they must explore energy transition strategies, including heat recovery, fuel substitution, or carbon capture, to reduce CO_2 emissions. This paper evaluates the potential of energy transition in these sectors through case studies, using a mixed integer linear programming (MILP) approach. The analysis focuses on three key performance indicators (KPIs): specific energy consumption, CO_2 reduction, and variable costs. By 2050, the adoption of heat pumps and waste valorization emerge as the most promising solutions for the syrup and laundry sectors. Specifically, the use of heat pumps reduces energy demand by at least 50%, while on-site biofuel production can fully replace natural gas consumption, thus eliminating dependency on external energy sources. The analysis highlights the importance of sector-specific strategies to meet climate targets, offering a pathway for low-temperature heat industries to reduce emissions while addressing economic and technological constraints.

Keywords: Energy Management, Process Design, Energy Systems, Alternative Fuels, Renewable and Sustainable Energy

1. INTRODUCTION

The goal of achieving net zero emissions by 2050 has driven European industries to intensify their efforts toward implementing CO_2 reduction strategies. While hard-to-abate sectors like steel, cement, glass, and lime production, etc., characterized by high-temperature energy demands, are the focus of much attention, other sectors characterized by lower emissions and typically low to moderate temperature heat demands are often overlooked. However, these sectors collectively contribute a substantial share of the total industrial emissions of a country [8]. The potential of energy transition to low-emission pathways in these sectors needs to be detailed.

In this study, two low-temperature (low-T) industries, syrup manufacturing, and laundry, are selected as case studies to demonstrate a methodological approach for addressing the energy transition in low-T industries. Key strategies leading to reduced emissions in such industries include heat recovery (via Heat Pumps), fuel substitution (e.g., hydrogen, biofuels), electrification (electric boilers), and CO_2 capture (CC). Previously, other research also explored energy transitions in low-T industries [2][5]. Lastly, Best Available Techniques (BAT) documents also provide valuable insights into how such industries can reduce energy consumption (European Commission. Joint Research Centre, 2019). Although previous research tried to explore the potential of these pathways for low-T industries, a comprehensive techno-economic comparison, ranking these technologies from a future energy scenario point of view, is still lacking.

This study examines the potential energy savings and required investments associated with various energy transition strategies in low-T industries through a detailed techno-economic comparison. Multiple energy transition pathways, including fuel switching, CC, electrification, and heat recovery, are evaluated using key performance indicators (KPIs) such as relative energy consumption, total emissions, and total cost. Furthermore, a superstructure-based optimization is conducted to rank these pathways under different future energy scenarios, which dictate the prices of energy commodities and emissions. This comprehensive approach provides a robust analysis, supporting informed decision-making to identify the pathways that will play a crucial role in reducing emissions in low-T sectors under future scenarios.

2. METHODOLOGY

2.1 Process Description

This study analyzes two key sectors: laundry and syrup production, selected from industries located in the Liège Province, Belgium. By focusing on one food industry and one sanitation-related industry, the analysis highlights sector-specific opportunities for transitioning to more sustainable energy solutions.

The **laundry sector** cleans textiles using water, air, and energy. A standard cleaning cycle includes prewashing (30-45°C), washing (45-60°C), rinsing (20°C), spinning, and drying (70-120°C). For healthcare textiles, an additional disinfection step (60-90°C) may be incorporated, achieved through thermal treatment or chemical agents. When chemical disinfection is used, a neutralization stage is required to restore fabric pH, followed by rinsing to remove residual chemicals before spinning and drying. Washing typically employs hot water, heated directly by natural gas (NG) boilers or indirectly via steam through heat exchangers, while cold water is used during rinsing to remove detergent residues. Drying occurs in two phases: mechanical dewatering (spinning or compression) followed by thermal drying, where hot air, often heated by steam, removes the remaining moisture from the textiles [1].

The **syrup production** sector, which can be linked to the sugar industry, is more complex regarding its processes. Two types of syrup can be considered: one made directly from fruit and the other from cereals. The primary distinction between these two lies in the intermediate process. The fruit-based syrup requires cooking, while the cereal-based syrup involves hydrolysis. In both cases, it begins with the cultivation and harvesting of crops. In the plant, the initial step involves preparing the raw materials—either washing, cutting, or milling—requiring electricity consumption [10]. Then, both hydrolysis and cooking demand an energy source to achieve a medium temperature of approximately 100°C. Following these steps, the product undergoes filtration, typically involving mechanical technologies like decantation. The filtrate is then concentrated (80-120°C), transforming the fruit juice or cereal mixture into syrup. The common method for juice concentration is evaporation, particularly quadruple-effect evaporation [9]. This technology reduces energy demand for evaporation by approximately four times, as it recycles the energy from the produced steam. This step is nevertheless energy intensive. Finally, refining (105°C), cooling (65°C), and packaging (65°C to 15°C) can occur.

2.2 Superstructure Development

To conduct the optimization analysis, a general superstructure is developed for both industries, incorporating many possible energy transition options. Blueprints (BPs) are first created as equation-based models that include detailed mass and energy balances, as well as cost parameters for each process. These BPs are derived from BAT documents and relevant literature. BPs for all processes in both industries, along with available energy transition options, are integrated into the superstructure.

The superstructure contains the following options for energy transition in both sectors; 1) Heat recovery (via utilization of heat pumps, recovering heat from external and internal sources), 2) Fuel-switching (bio-fuels and H_2) 3) Electrification and cogeneration 4) Solid and Liquid waste valorization and 5) CC.

The energy demand in the syrup and laundry sectors is primarily met using NG boilers and electricity. Therefore, the base case configuration for each sector involves a NG-fired boiler with an assumed efficiency of 80% for steam generation. Both can implement fuel substitution, electrification, heat recovery, and CC.

There is considerable flexibility in the choice of fuel for boilers, with options including hydrogen, biomass, biogas, and other alternatives to reduce CO_2 emissions associated with NG combustion. Additionally, these boilers can be electrified to achieve similar outcomes. Liquid waste can be treated in water treatment units, where biogas is recovered through anaerobic digestion. Given that water treatment plants are already required in both sectors, biogas is readily accessible. For the syrup sector, solid waste, such as peels, rooted feedstocks, and cereal residues, can be composted to produce biomass. This biomass can either be used as a solid fuel for boilers or as an input for biomethanation. Through biomethanation, organic matter is converted into a combustible biogas, which can be further refined into biomethane. However, solid waste is often prioritized for reuse in crop cultivation, which may limit its availability for energy production. Bio-sourced fuels, regardless of their origin, can thus supply boilers, reducing the reliance on fossil fuels. Additionally, the produced gases can be used to power cogeneration units, thereby improving overall energy efficiency.

Heat recovery is another important option for these sectors. It can be achieved through heat pumps (HP),

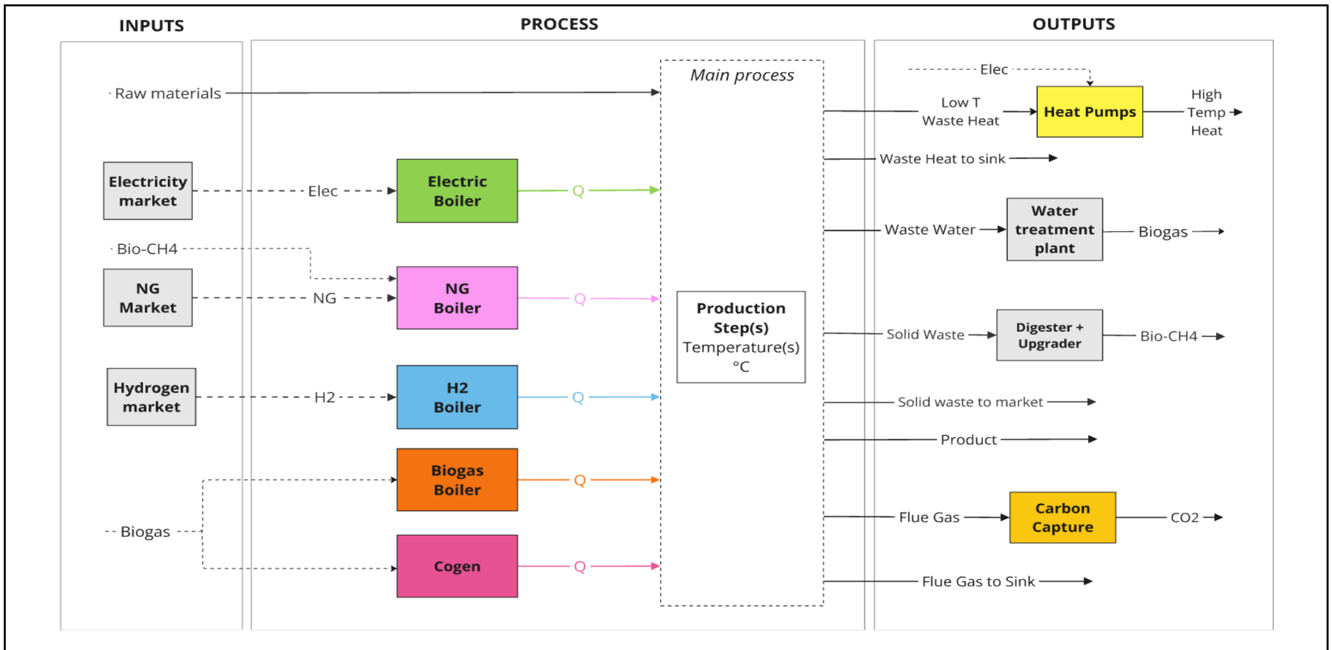

Figure 1. A general superstructure for the energy transition

which capture and reuse waste heat, further optimizing energy performance. Depending on the availability of a heat source inside or outside of the process, these are described as internal or external HP.

Lastly, the potential role of CC should be considered: if NG boilers are retained, CC may be necessary to achieve net-zero emissions by 2050. In this context, CC refers to a post-combustion capture process based on chemical absorption using amine solvents.

Figure 1 illustrates a general superstructure for the energy transition in these sectors incorporating all the options discussed above.

Assumptions are made regarding the efficiency and performance of key technologies. For fuel substitution, it is assumed that green electricity operates with an energy efficiency of 90–100%, while green hydrogen is characterized by an energy density of 34 MWh/t with an energy efficiency close to 90%. Biofuels such as biomass and biogas, are considered less efficient, with a thermal efficiency of 70% [3]. In the context of heat recovery, HP functioning within a temperature range of 100°C to 200°C are expected to achieve a coefficient of performance (COP) ranging between 2 and 3 [12]. For CC, post-combustion technologies are assumed to capture at least 90% of CO_2 emissions, with energy requirements estimated between 0.9 and 1.4 MWh/t of CO_2 captured [6].

2.3 Optimization Problem and KPIs

Once the superstructure is developed, the next step is to solve the optimization problem. For this, the Osmose Lua optimization framework [11]. a tool to optimize process and energy systems, is utilized to solve mixed-integer linear programming (MILP)-based formulation containing objective functions of total specific cost and emissions. It optimizes the superstructure of the BPs models, serving as a decision-support tool to identify the most effective CO_2 reduction strategy tailored to each sector's specific needs.

The evaluation of various strategies for each sector is based on three KPIs: specific CO_2 emissions, specific energy consumption, and specific variable costs.

The two objective functions employed for the evaluation are specific variable cost (€/t of materials) and specific emissions (tCO_2//t of materials) and the MILP problem to be solved is outlined in equations (1-4).

$$Annual\ CAPEX_{n,i} = \sum_u \left(CAPEX(u_{ref}) \cdot \left(\frac{s}{s_{ref}}\right)^{0.6} \cdot \frac{CEPCI_{2023}}{CEPCI_{ref}} \cdot i \cdot \frac{(i+1)^n}{(i+1)^{n-1}} \right) \quad (1)$$

$$Annual\ OPEX = \sum_u \left(\sum_e \left(C_{e_u} \cdot \dot{Q}_{e_u} \right) + \left(C_{em_u} \cdot \dot{m}_{em_u} \right) \right) \cdot hr \quad (2)$$

$$\min Cost \left(\frac{€}{ton\ of\ material} \right) = \frac{Annual\ OPEX + Annual\ CAPEX}{ton\ of\ product\ per\ year} \quad (3)$$

$$\min Emissions \left(\frac{ton\ of\ CO_2}{ton\ of\ material} \right) = \frac{\sum_u (\dot{m}_{em_u}) \cdot hr/1000}{ton\ of\ material\ per\ year} \quad (4)$$

CAPEX is annualized over 25 years (n) with a 3% discount rate (i), u is the unit, s the unit size, ref the reference unit for CAPEX calculations. For OPEX calculation, C represents cost, e the energy source, $\dot{Q}$ energy, $\dot{m}$ mass flow rate, em emissions, and hr total operating hours (8000). CAPEX excludes constant equipment costs across configurations, and OPEX omits raw material costs, as they remain unchanged.

Equation (2) treats energy and emission costs as input variables, based on future energy projections. The electrification scenario from EnergyVille's Paths2050 study (TIMES-BE) has been selected to provide marginal production costs for electricity, hydrogen, and natural gas, along with CO_2 emission costs [7]. This choice favors renewable energy and more particularly electricity use. Table 1 gives a detailed view of the cost. Carbon taxes are evaluated at 350 €/tCO_2 for 2050.

Table 1: Marginal production costs of energy commodities, based on the Paths2050 study electrification scenario for 2050 [7]

Price (€/MWh)	Electricity	H_2	Natural Gas
	56	78	35

3. RESULTS AND DISCUSSIONS

3.1 Blueprint Validation

Table 2 compares the specific energy consumption derived from the BPs and the data available in the literature. The calculated values fall within the range reported in the literature, confirming the validity of the mass and energy balances for the syrup and laundry sectors.

Table 2: Specific energy demand comparison for BPs model and literature [1] [4]

Sector	Unit	BP model	Literature
Syrup	MWh/t fruits-cereals	0.23-0.26	[0.05; 0.6]
Laundry	MWh/t laundry	2.21	[1.3; 4.6]

3.2 KPI evaluation

First, the specific energy demand and Scope 1 emissions for the laundry and syrup sectors are analyzed for each pathway toward achieving net-zero emissions. The results are presented in Figure 2.

In the laundry sector, the base case scenario consumes 2.21 MWh/t of laundry and generates 0.4 tCO_2/t of laundry. Transitioning to hydrogen or electrification results in similar energy demands, with less than 10% variation, due to comparable efficiencies with NG. Nevertheless, electricity and hydrogen offer the advantage of eliminating Scope 1 emissions. Biogas has the same advantage (as it gives biogenic emissions that are not accounted for) but leads to a 20% increase in energy demand compared to NG boilers. In contrast, the laundry sector can adopt CC without going for fuel substitution. This approach results in the highest energy demand but still emits approximately 10% of the CO_2 produced from NG, due to capture efficiency. Lastly, external HP use reduces the base case energy consumption by more than half, achieving 0.87 MWh per ton of product, while maintaining zero Scope 1 emissions. Alternatively, a simple electrification with no HP also decreases energy demand (but to a lower extent) and reaches zero scope 1 emissions. In conclusion, for the laundry sector, heat recovery offers the greatest benefits: HP strongly reduce energy demand, also decreasing Scope 2 emissions associated with electricity consumption.

For the syrup sector, the base scenario depicts an energy consumption of 0.26 MWh/t of cereals and 0.05 tCO_2/t of cereals. Among the transition pathways, the highest energy demand is associated with CC, then NG substitution by biogas, primarily due to the relatively low efficiency of biogas considered in this study. These paths increase energy consumption by at least 20% while achieving CO_2 emission reductions of 50% to 90% compared to the base case. Conversely, the lowest energy demand is linked to internal HP utilization with NG, resulting in a 65% reduction in energy demand. To combine energy consumption reduction while minimizing reliance on NG, HP can also be coupled with cleaner energy sources such as electricity, hydrogen, or biogas. The valorization of biogas from biodigesters, when combined with HP, already achieves a 15% reduction in energy consumption and eliminate Scope 1 CO_2 emissions. In the food industry, internal HP enable heat recovery from the cooling process to warm water for cooking purposes. More particularly, quadruple effect evaporation exhibits advantages for HP use. The use of electricity and hydrogen eliminates Scope 1 emissions while maintaining energy consumption levels close to the base case, with only a 5% to 10% variation.

Next, the economic results are discussed. Figure 3 provides the installation and operational costs associated with deploying new units in the laundry and syrup sectors for each pathway. The variable costs linked to the operation of NG boilers in the base case scenario are calculated at 230 €/t for laundry processing and 29 €/t for cereal production. The laundry sector demonstrates the lowest operational costs when utilizing biogas (93% reduction). Biogas is assumed to be produced and used onsite, incurring mainly capital costs for the digester and minimal operating expenses. The laundry sector is expected to integrate biogas production within its existing wastewater treatment plants, which should generate sufficient biogas to meet energy demands. A sensitivity study should be done to assess plant capacity, validate biogas availability, and refine energy requirements for anaerobic digestion, where additional costs are primarily limited to electricity for mixing and pumping. Following biogas, electricity use also demonstrates greater cost-effectiveness compared to the base case scenario, resulting in a cost reduction of nearly 50% with electrification and up to 70% with the integration of HP, despite their higher capital investment compared to conventional boilers. This observation aligns with the 2050 "EnergyVille" scenario proposed by VITO, which prioritizes electrification as a key pathway for defossilisation. In contrast, CC is the least economically favorable option. The laundry sector's has a relatively low CO_2 emissions capacity, resulting in an increase in the specific capital expenditure per ton of CO_2 captured. In comparison with considering the cost of CO_2 allowances, the investment required for CC remains too high to be economically viable for this sector.

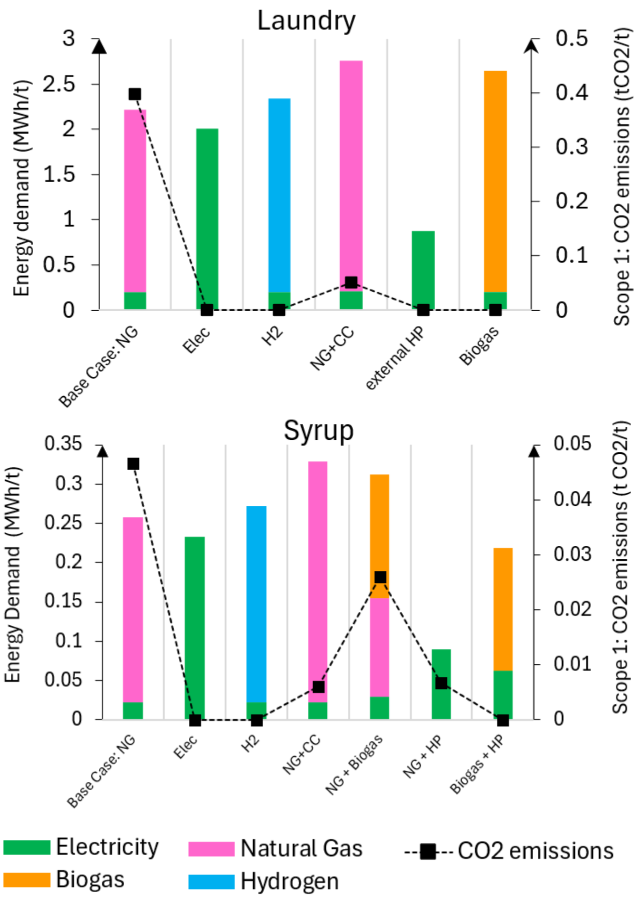

Figure 2. Specific energy consumption and CO_2 emissions in the laundry and syrup sectors based on energy choices

The analysis of the syrup production sector reveals conclusions analogous to those observed in the laundry sector. Biogas and electricity exhibit the lowest production costs among the evaluated energy sources.
Biogas is still considered to be derived from solid waste, leading to low additional cost, while electricity remains more economical than both hydrogen and NG. CC is slightly more economically viable in the syrup sector compared to the laundry sector. This is primarily attributed to the production scale, which generates approximately 86,000 tons of CO_2 per year for syrup production, in contrast to 4,000 tons of CO_2 per year for the laundry sector. Given this higher volume of emissions, CC is more cost-effective than purchasing CO2 quotas, with a 34% cost reduction compared to the base case.

Overall, based on the KPI analysis, the transition strategies for the sectors under study are highlighted.

The analysis identifies bio-based resources and electrification as the most viable pathways, given their low to moderate process temperature requirements.

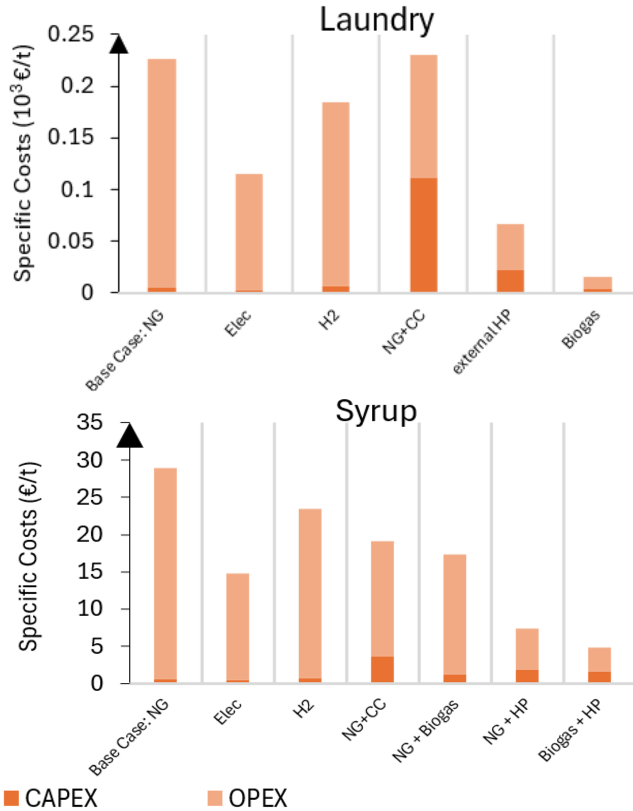

Figure 3. Specific costs in the laundry and syrup sectors based on energy choices

Fuel substitution emerges as a viable alternative for the transition. Each form of fuel substitution eliminates Scope 1 CO_2 emissions, with the most economically advantageous option being the valorization of solid or liquid waste to produce biogas, even if it requires more energy. In addition, electrification and HP integration present major opportunities for energy transition. Electrification provides higher energy efficiency compared to NG or hydrogen-based systems while eliminating direct CO_2 emissions. HP further enhance this advantage by enabling efficient waste heat recovery, reducing overall energy consumption.

Sector-specific differences can still be addressed. In the syrup sector, internal HP are used to recover on-site waste heat, and their efficiency is modeled using Carnot assumptions. Conversely, the laundry sector employs external HP, for which a COP of 3 is assumed, reflecting typical temperature lifts from an ambient temperature source of 20°C to a process requirement below 120°C. As COP values vary according to process conditions, their fluctuation directly impacts the electricity consumption of HP. While unfavorable COPs can increase electricity use, ongoing technological advancements are expected to improve COP, enhancing the efficiency and cost-effectiveness of this approach.

4. CONCLUSIONS & PERSPECTIVES

This study explores the transition pathways for the laundry and syrup sectors toward net-zero emission objectives using the Osmose Lua optimization framework based on MILP. Energy transition strategies analyzed hydrogen utilization, bio-based resources, electrification, CC and HP integration.

Bio-based fuel substitution is particularly relevant for sectors with low-T demand when on-site resources, such as wastewater or solid waste, can produce biofuels, enabling direct reductions in Scope 1 CO_2 emissions. Electrification and HP integration offer efficient, cheap, and clean alternatives to fossil fuel use, with facilitating waste heat recovery in the case of HP. Technological improvements in HP, especially in COP, could further enhance its competitiveness. Hydrogen, while efficient and CO_2-reducing, faces barriers like infrastructure needs (facility retrofitting, revaluation of transport, storage logistics) and high costs, making it less viable for low-temperature sectors. H_2 and CC are deemed less favorable options for the future of the low-T sector. The substantial capital expenditures required for CC are disproportionate relative to the moderate emissions levels of the industries.

As a result, to achieve net-zero Scope 1 emissions in low-temperature industrial sectors by 2050 will likely require a multi-pronged approach combining bio-based fuel substitution, HP integration, and/or electrification. Looking ahead, Effective strategies will depend on sector constraints and energy price trends, with continuous reassessment and scenario-based planning crucial for identifying viable pathways.

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