Industrial Brownfields and Their Potential in Decarbonization of Production and Logistical Processes

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ABSTRACT

Article quantifies and compares the environmental impacts of operating repurposed industrial brownfields versus modern greenfield logistics centers. While the construction of new warehouse complexes is an essential component of supply chains, it entails the permanent loss of high-quality agricultural land and negative impacts on the local hydrological regime. Using Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA) methodologies, the research analyzes the specific revitalized wood-processing site of JUGAST Ltd., which is situated in the village of Obišovce (Slovak Republic).

The results of the comparative analysis demonstrate that the technological adaptation of existing sites minimizes the environmental footprint associated with the construction phase and land take. The article further quantifies stormwater runoff patterns and proposes the implementation of strategic innovations - such as the integration of photovoltaic and water retention systems - aimed at achieving comprehensive energy and environmental operational self-sufficiency.

KEYWORDS: *brownfields, warehouse complexes, environment, LCA, decarbonization, circular economy*

INTRODUCTION

The dynamic development of logistics and e-commerce in the 21st century has triggered an unprecedented expansion of industrial infrastructure [1]. This growing demand for warehouse space is primarily met through greenfield development. However, from the perspective of spatial planning and environmental engineering, this extensive model entails significant environmental externalities. Modern logistics centers require vast surface areas, resulting in the permanent loss of agricultural land, the widespread sealing of surfaces with impermeable materials, and the creation of urban heat island effects.

Standing in direct contrast to this approach is the concept of a circular economy and sustainable land management, which prioritizes the revitalization of older, often underutilized industrial sites. Adapting these historically urbanized areas eliminates the need to convert additional agricultural land and allows for the productive reuse of existing infrastructure. The central research issue is the growing conflict between the dynamic expansion of logistics infrastructure and the requirements for environmental protection, sustainable land use, and energy self-sufficiency. This article aims to verify theoretical assumptions regarding brownfield sustainability through the application of analytical tools. Using the JUGAST Ltd. site as a case study - a facility comprising not only production operations (sawmilling and subsequent wood processing, such as briquetting) but also extensive storage areas—the article identifies critical points of environmental impact. This combination of production and storage functions allows for a comprehensive comparison between this revitalized site and newly constructed greenfield logistics centers. Subsequently, the article analyzes the facility's technological level and compares its hydrological and energy parameters against modern logistics standards.

Assessment Methodology and Definition of System Boundaries

To objectively assess environmental impacts, a combination of retrospective impact assessment and life cycle asessment methodology was selected. This integrated approach makes it possible to quantify not only direct local impacts on the land but also the broader emissions and energy footprint of the operation.

Applied Standards and Life Cycle Inventory

The assessment was structured in accordance with international standards ISO 14040 and ISO 14044 [2]. To conduct an in-depth analysis of environmental and energy impacts, the study focused primarily on the operational phase of the life cycle, which accounts for the largest share of emissions in older industrial complexes. During the inventory phase, actual operational data were collected and evaluated for the repurposed brownfield site (originally constructed in 1958), which has a total area of 13,592 m². The input analysis focused on primary energy consumption, with the facility's average monthly electricity consumption amounting to 5,500 kWh. The outputs were quantified in terms of the total emissions footprint, taking into account the dominant impact of electricity consumed from the distribution grid. These values were subsequently compared with benchmarks from modern logistics centers.

Mathematical Model for Assessing Hydrological Impacts

A key indicator of an industrial site's environmental friendliness is its ability to manage precipitation at the point where it falls. Extensive soil sealing at modern logistics centers transforms natural infiltration into immediate surface runoff. To precisely quantify the analyzed site's impact on the local hydrological cycle, a weighted arithmetic mean of the runoff coefficient was calculated. This parameter is defined by the following equation:

$$\Psi average = \frac{\sum(An \cdot \Psi n)}{\Sigma An}$$

Here, the quantity A_n represents the surface area of a specific type of surface within the site (in m²), and the quantity Ψn represents the dimensionless runoff coefficient associated with that surface. This mathematical model precisely expresses the ratio between the volume of water running off the surface and the volume of water falling upon it [3]. It thus enables a direct comparison of the retention capacity of a revitalized brownfield - which combines historical paved areas with extensive grassed areas - against the fully sealed surfaces of modern greenfield projects.

Application of a hydrological model and quantification of rainwater retention

Following the established methodology, the weighted arithmetic mean of the runoff coefficient was calculated using actual spatial parameters from the revitalized JUGAST Ltd. brownfield site. For

the purpose of the calculation, the site's total area of 13,592 m² was categorized into three functional units based on their physical and surface characteristics: impermeable roof structures of the halls, covering an area of 500 m² with a standard runoff coefficient of $\Psi = 0.90$. Existing paved surfaces (concrete panels and asphalt) exhibiting micro-cracks, covering an area of 5,000 m² with a coefficient of $\Psi = 0.70$. And finally biologically active, extensively grassed areas that are covering 8,092 m² with a coefficient of $\Psi = 0.20$. Applying the aforementioned equation yielded a weighted average runoff coefficient of approximately $\Psi_{average} \approx 0.41$ for the analyzed site. This quantitative result conclusively demonstrates that the presence of existing semi-permeable surfaces and a substantial proportion of extensive greenery enables the site to infiltrate nearly 60% of precipitation directly at the point of impact. Standing in direct contrast are modern greenfield logistics centers, which - due to extensive surface sealing (asphalt handling areas, vast roofs made of PUR panels) - generate critical values of $\Psi \geq 0.90$. The high level of natural retention found in an adapted brownfield site serves a dual environmental function: it ensures the continuous recharging of groundwater horizons and actively contributes to the microclimatic stability of the surrounding area through evapotranspiration, thereby preventing the formation of industrial heat islands.

Spatial Optimization and Protection of Agricultural Land Resources

Another indicator of environmental impact monitored during the assessment process was the consumption of land resources - defined in international terminology as "Land Take" [4]. The rapid expansion of logistics centers typically involves the permanent conversion of high-quality agricultural and forest land, resulting in the immediate and irreversible loss of the soil's biological, filtration, and productive functions at the construction site. An analysis of the JUGAST facility regarding this parameter shows zero new demand on agricultural land resources (0 m²), as the operation fully utilizes the existing infrastructure of a former agricultural cooperative established in 1958. From a spatial planning perspective, the new development does not result in the sealing of the land surface, allowing the surrounding rural landscape to retain its ecosystem services (particularly carbon sequestration and biological production potential). Furthermore, the sensitive integration of the original buildings into the existing terrain and the presence of surrounding vegetation ensure an organic visual blend with the landscape, thereby avoiding the landscape fragmentation typical of uniform logistics warehouses with high attics situated in open areas.

Material footprint and life-cycle assessment (LCA) of embodied emissions

When evaluating the life-cycle stages, the structural fabric of both models was subjected to a comparative analysis. The fundamental difference lies in material diversity and structural service life. Traditional brownfield (JUGAST Ltd.): The complex utilizes massive structures (fired brick, lime plaster) that exhibit exceptional mechanical and structural durability. Under the LCA methodology, the primary emissions associated with the original construction are amortized over a period of nearly 70 years, thereby reducing the building’s annualized carbon footprint to a theoretical minimum. This represents an efficient use of so-called embodied carbon, as there is no need to produce new building materials (such as cement and steel, which are highly energy-intensive to manufacture). *Modern logistics center:* While structures based on steel and polyurethane (PUR) sandwich panels allow for rapid assembly, their design service life is significantly shorter (typically 20 to 25 years). In addition to the high initial carbon footprint associated with their production, these composite materials pose a significant environmental risk at the end of the building's life cycle, as separating and recycling them is technologically challenging. By utilizing an existing brownfield site, the entity de facto effectively recycles an entire industrial building, representing the highest form of circular economy application in the construction sector [5].

Analysis of Energy Flows and Technology Emission Footprints (Scope 1 and Scope 2)

Within the framework of standardized life cycle assessment (LCA) methodology, the inventory phase constitutes a key analytical step for the precise quantification of inputs and outputs, with a primary focus on greenhouse gas emissions. For a comprehensive assessment, energy flows were categorized

according to the internationally recognized Greenhouse Gas Protocol standard. The analysis revealed a significant energy paradox in the operation of the repurposed brownfield site, a factor that directly determines the enterprise's overall environmental profile.

Heat Management and Carbon Neutrality (Scope 1)

In the category of direct emissions (Scope 1, emissions that are generated locally at the site of operations), the facility under review demonstrates a high degree of material synergy and energy resilience. During the winter months, heating needs of the facility are fully met by utilizing certified biomass made as by-products from the company's own wood processing operations (sawdust, offcuts, and bark).

Under the international methodology of the Intergovernmental Panel on Climate Change (IPCC), these emissions are accounted for as zero, as the released carbon dioxide (CO_2) is an integral part of the short-term carbon cycle. This closed-loop circular model completely eliminates JUGAST's operational dependence on fossil fuel supplies. In direct contrast, modern logistics centers typically rely on the widespread combustion of natural gas (e.g., via gas-fired radiant heaters and gas boilers), which continuously generates fossil carbon emissions and significantly increases their environmental debt according to Scope 1.

Electricity Consumption and Technological Debt (Scope 2)

A significant environmental and economic conflict was identified regarding electricity consumption, which falls under the category of indirect emissions (Scope 2). Operations at the repurposed brownfield site rely entirely on the external distribution grid; with an average monthly consumption of 5,500 kWh, the facility ranks among energy-intensive enterprises. An analysis of consumption patterns revealed that up to 75% of this usage is directly linked to production activities and the operation of heavy machinery (asynchronous electric motors for saws, large-scale extraction systems, and briquetting presses). The remaining 25% is accounted for by support facilities, administration (10%), and lighting (15%) – see Fig. 1.

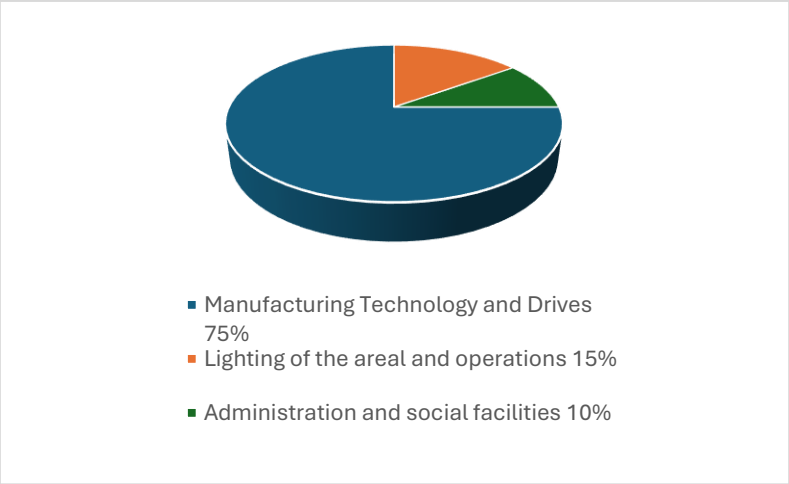

Fig.1. Breakdown of average monthly electricity consumption (5,500 kWh) by key operational nodes within the facility

A specific characteristic of this technological equipment is its discontinuous power consumption profile. Direct starting of heavy-duty machinery without variable frequency drives (using the so-called star-delta method) results in extreme current spikes, reaching up to 125 kW at the start of a work shift (see Fig. 2).

These surge loads place excessive mechanical and electrical stress on the internal grid and generate high fixed costs for reserved capacity from the distributor, even though the average operating load during steady-state operation is only around 70 kW. This technical debt creates an operational paradox: otherwise highly eco-friendly processes - such as central sawdust extraction systems that preserve local air quality or the production of bio-briquettes themselves - are powered by more expensive electricity from the grid.

Although Slovakia's national energy mix is primarily low-carbon (dominated by nuclear power at approximately 62% and hydropower at 17%), fossil fuels (particularly natural gas and coal) still account for around 14% of the total. Consequently, the lack of an in-house renewable energy source (only 7% of the total) continues to impose an emissions burden on the company and contributes to its carbon footprint.

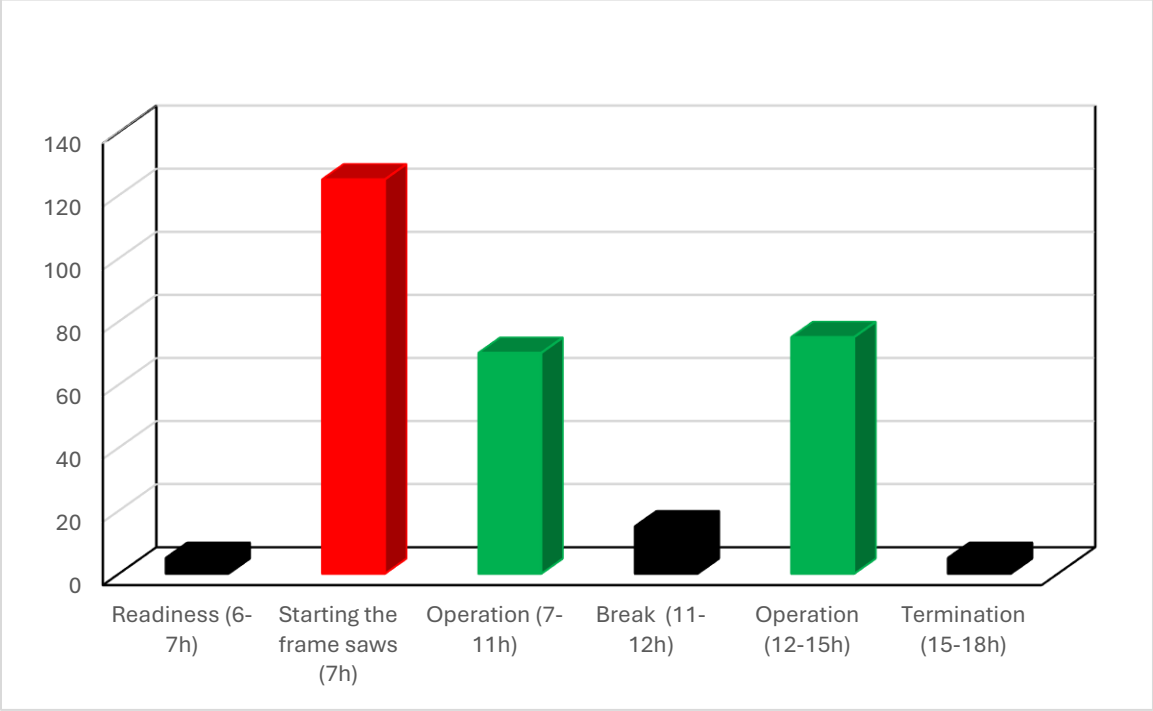

Fig. 2. Daily load profile demonstrating extreme current surges during the startup of heavy-duty synchronous equipment (so-called "technological debt")

Comparative Analysis of Consumption Profiles

The consumption curve of the adapted JUGAST Ltd. brownfield site (in Obišovce) stands in stark contrast to the characteristic energy profile of modern automated logistics centers. While the production facility in Obišovce operates on a strict single-shift daytime schedule - remaining technologically inactive and drawing almost no power after work hours (especially at night) - modern greenfield distribution projects are characterized by a profile of extreme, continuous energy demand on a 24/7 basis. The low thermal inertia and insulating properties of lightweight PUR panels necessitate the continuous operation of HVAC (Heating, Ventilation, and Air-Conditioning) systems to maintain the indoor climate in these new halls. This factor, combined with the constant power demand of automated intralogistics lines, refrigeration units, and extensive area lighting, creates a massive and continuous base load on the electrical grid. The combination of utilizing natural daylight in older brick buildings, natural thermal regulation and cooling provided by massive walls, and the complete absence of night-time operations results in the revitalized brownfield site achieving significantly lower annual and area-specific energy intensity (kWh/m²). However, the successful completion of the site's sustainable transformation inevitably requires a direct technological solution to address the identified reliance of motor units on the external grid and to eliminate the aforementioned startup power spikes.

Supply Chain Decarbonization and Scope 3 Emission Management

A comprehensive life-cycle assessment (LCA) of industrial and logistics facilities cannot be limited solely to internal technical and environmental indicators. An equally important pillar of sustainability is the extent of a facility's interaction with transport infrastructure and the associated indirect emissions within the supply chain (defined as Scope 3 under the international GHG Protocol standard). In this regard, comparative analysis reveals a fundamental difference in logistics models. Modern logistics parks demonstrate a near-absolute spatial and operational correlation with highway corridors. This model, known as the "carbon lock-in" phenomenon, ties supply chains exclusively to road freight transport [6]. Consequently, these centers generate a constant traffic burden and a high emissions footprint, with the average emission intensity of road freight transport (truck combinations exceeding 24 tonnes) reaching approximately 62 g of CO_2 per tonne-kilometer. In stark contrast, the revitalized JUGAST Ltd. complex enjoys a strategic comparative advantage due to its immediate proximity to the major Kysak railway hub (a first/last-mile distance of just 2.2 km). This locational attribute enables the facility to implement intermodal transport principles. In this model, rail transport serves as the low-emission backbone for high-volume shipments, while road transport is limited exclusively to local last-mile operations.

Quantification of the environmental benefits of modal shift

From an environmental engineering perspective, shifting freight flows from road to the electrified rail network represents one of the most effective decarbonization tools. Given Slovakia's energy mix, electrified rail traction exhibits an emission intensity of just 15 g CO_2/tkm. Leveraging this multimodal potential directly reduces the distribution process's carbon footprint by more than 75% compared to the monomodal road alternative typical of modern greenfield sites. Moreover, in addition to reducing greenhouse gas emissions, this modal shift eliminates significant negative externalities within the built-up areas of the affected municipalities - specifically particulate matter emissions from tire and brake wear, chronic noise pollution, and the accelerated deterioration of local roads. The ability of this historic brownfield site to integrate into the rail network thus makes it a far more sustainable and socially acceptable model for a logistics hub compared to isolated distribution centers reliant on road freight.

Acoustic Pollution Analysis and Microclimatic Barrier

An integral part of the comprehensive scientific assessment of the environmental impact of industrial and logistics complexes is the precise quantification of acoustic pollution and its dispersion into the surrounding area. Noise exposure is one of the most critical factors affecting the quality of life for residents in adjacent communities and has a direct negative impact on local fauna. In this context, a comparative analysis reveals significant differences in the temporal and spatial profiles of noise emissions among the models evaluated.

Modern greenfield logistics centers generate continuous, 24-hour acoustic loads. The equivalent sound pressure level (L_{Aeq}) here is constantly driven by a combination of static and dynamic sources. Static sources include the continuous operation of large roof-mounted air-handling and cooling units, while dynamic sources comprise the constant movement of heavy freight traffic, the audible reversing alarms of vehicles, and the operation of trailer-mounted refrigeration units during night shifts. Furthermore, the location of these halls in open, flat terrain devoid of natural obstacles facilitates the unobstructed spread of sound waves over long distances.

The revitalized JUGAST Ltd. wood-processing brownfield site is characterized by a radically different acoustic profile. Since the primary wood-processing technology generates high instantaneous sound power levels - stemming from the operation of gang (frame) saws, wood chippers, and pneumatic extraction systems - operations are strictly limited to a single-shift daytime schedule. During nighttime hours and non-working days, the site produces zero acoustic emissions, thereby ensuring compliance with strict noise regulations for protected outdoor areas and avoiding disruption to the local community's circadian rhythms.

Terrain Absorption and Vegetative Barriers

A key factor in preventing the spread of operational noise from the brownfield site to the surrounding area is its spatial integration. The site is situated within undulating, sloping terrain and is directly bordered on two sides by a dense mixed forest. This topography acts as a massive, natural noise barrier. From the

perspective of architectural acoustics, the high density of surrounding biomass (leaves, trunk structures, and forest soil) results in a high sound absorption coefficient (α) [7]. Thus, the vegetation not only visually segments the site but also actively attenuates the spread of high-frequency industrial noise through the multiple scattering and diffraction of sound waves. From the perspective of acoustic urbanism, the revitalization and use of such strategically located brownfields therefore represent a significantly more sensitive approach to the surrounding landscape compared to the construction of new industrial halls, which often require the installation of artificial noise barriers along transport routes.

Proposal of Technological Innovations for Sustainable Operations

Based on the results of a comprehensive environmental impact assessment, it can be concluded that although the revitalized JUGAST Ltd. brownfield demonstrates a high degree of spatial and ecological sustainability (zero land take, high water retention, Scope 1 carbon neutrality, and noise pollution mitigation), its overall environmental profile is compromised by the technological debt associated with older infrastructure. To achieve fully climate-neutral and cost-effective operations, it is essential to implement targeted engineering measures that eliminate the identified energy anomalies within the Scope 2 category.

Tab. 1. Comparison table of brownfield vs. greenfield

	Revitalized brownfield (JUGAST Ltd.)	**Modern Logistics Center (Greenfield)**
Land Take	0 m^2 (redevelopment of historical infrastructure)	Extensive and irreversible loss of high-quality agricultural land resources
Rainwater retention	Excellent $\Psi \approx 0.41$; (infiltration of nearly 60% of totals)	Critical $\Psi \geq 0.90$; (massive surface runoff)
Annualized carbon footprint of materials	Minimized (structural service life of approx. 70 years)	High (shorter service life of PUR structures)
Heat management (Scope 1)	Circular (zero-emission biomass recovery)	Externally dependent (natural gas combustion)
Energy profile (Scope 2)	Intermittent daily withdrawal (high start-up peaks)	Continuous offtake (24/7) with a massive baseload
Acoustic environmental load	Strict daily operation with terrain and vegetation absorption	Continuous noise emission from stationary/dynamic sources

Application of intelligent frequency control and peak load elimination

A primary operational challenge involves extreme current surges - reaching up to 125 kW - generated by the direct-on-line starting of massive asynchronous electric motors powering gang saws and extraction systems. Consequently, the proposed primary technical measure is the comprehensive implementation of intelligent frequency control systems across all key rotating units. From an electrical engineering perspective, the deployment of variable frequency drives (VFDs) ensures a "soft start," completely eliminating high inrush currents through the controlled adjustment of frequency and voltage. Mathematical modeling of this measure demonstrates a 60 - 70% reduction in instantaneous starting power, thereby stabilizing and leveling the facility's total power consumption curve to the nominal operating input of 70 kW. This step yields a threefold synergistic effect: (1) it drastically reduces fixed distribution charges for reserved grid capacity; (2) it lowers mechanical stress and wear on transmission components, thereby extending their service life; and (3) it utilizes sensor-based control to adaptively adjust the cutting speed to current conditions, which results in electric power saving within the 15–25%.

Integration of a Photovoltaic System and Energy Self-Sufficiency

The second strategic step is the decarbonization of the electricity source itself. Given the specific operational profile of the wood-processing brownfield site - which operates exclusively on a single-shift,

daytime schedule - there is an ideal alignment between the facility's power consumption curve and the curve of peak daily solar irradiance. To meet the stabilized load profile (achieved through the use of Variable Frequency Drives, or VFDs), the installation of a rooftop photovoltaic system with an installed capacity of approximately 75 kWp is proposed. Given the large surface area of the existing roofs (500 m²) and their favorable orientation, this output level is fully achievable without the need to utilize additional ground space. A key environmental and economic advantage of this proposal is the exceptionally high rate of immediate self-consumption of the generated energy (estimated to exceed 85%). Due to the absence of night-time operations, the system does not require the installation of costly large-capacity battery storage units (such as lithium-based systems) that pose environmental concerns. The physical transformation of the facility through the installation of a photovoltaic (PV) system directly ensures independence from the supplier's energy mix - which relies heavily on fossil fuels - thereby minimizing Scope 2 emissions to near-zero levels.

Synergy of Innovations and the Smart Brownfield Concept

The combination of frequency control (reducing and stabilizing energy consumption) and local energy generation via PV systems (covering this reduced demand with green energy) represents a model example of technological retrofitting. Following the implementation of these measures, the JUGAST facility is transforming from a traditional historic site into a so-called "Smart Brownfield" [8]. In this regard, the operation not only keeps pace with modern logistics centers in terms of energy efficiency but - thanks to inherent spatial and microclimatic advantages (water retention, biomass-derived heat, soil protection) - significantly outperforms them in terms of comprehensive environmental sustainability.

CONCLUSION

The results of the presented study open a critical discussion regarding the current paradigm of industrial and logistics infrastructure development. The prevailing development model, which favors large-scale greenfield construction, is often legitimized through the implementation of modern technologies and the acquisition of energy-efficiency certifications such as BREEAM or LEED. However, as a comprehensive life-cycle analysis has demonstrated, this operational efficiency is typically achieved at the cost of irreversible spatial and environmental externalities - specifically the sealing of high-quality soil, the drastic disruption of the local hydrological cycle, and the lock-in of supply chains to carbon-intensive road freight. Conversely, an approach based on adapting existing brownfields faces a primary obstacle in the form of the technological and energy debt associated with older infrastructure. However, the presented comparative analysis conclusively demonstrates that this operational debt (identified within the Scope 2 emissions category) - unlike the irreversible loss of ecosystem services - can be addressed in a technically and economically efficient manner. Targeted technological retrofitting, involving the installation of photovoltaic systems and intelligent variable-frequency drive controls, can successfully close this energy gap. The research findings confirm that, from the perspective of global environmental sustainability, the revitalization of older industrial sites represents a superior model to extensive new construction.

The case study of the JUGAST Ltd. complex demonstrated that preserving the existing building fabric minimizes the carbon footprint associated with embodied emissions and protects agricultural land resources. Combining natural stormwater retention, noise mitigation through surrounding vegetation, and the use of carbon-neutral biomass creates an exceptionally stable ecological foundation. When this foundation is complemented by proposed engineering measures to decarbonize electricity consumption and a strategic connection to a low-emission rail network, the result is a model of fully autonomous and climate-resilient operations. This integrated approach fully embodies circular economy principles and offers a viable strategy for industrial transformation aligned with the goals of the European Green Deal.

Consequently, the study's results and methodology provide not only an analytical tool for assessing the impacts of similar sites but also a clear recommendation for environmental policymakers and urban planners: to ensure the country's long-term sustainability, it is essential to prioritize and incentivize - through subsidies - the technological modernization of existing brownfields and multimodal hubs rather than approving further expansion of industrial and logistics infrastructure into the wild.

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