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Article

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Site Suitability Analysis for Carbon-Neutral Villages Based on Livestock Manure and Forest Biomass Through Geospatial Analysis

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Abstract: This study identifies suitable sites for carbon-neutral villages by utilizing livestock manure and forest biomass, key resources in rural areas, contributing to climate change mitigation and the achievement of national greenhouse gas reduction targets. For this purpose, nationwide public geospatial information and statistical data were analyzed using QGIS. First, 9,075 villages with a density of 50 or more households in areas lacking city gas supply were identified as potential candidates suitable for district heating. For the efficient utilization of livestock manure resources, the spatial distribution characteristics of livestock farms were quantified using the Average Nearest Neighbor Index (ANNI) and a Concentration Index (CNI), and then categorized into priority areas for biogas plant construction, areas requiring consolidation, and areas where livestock scale reduction is recommendable. Furthermore, to establish a stable supply chain for unused forest biomass, an analysis of the supply radius (50 km) of the five existing resource centers revealed significant supply gaps, leading to a proposal for nine new center locations. Finally, by spatially overlaying the availability of both livestock manure and forest biomass resources with the distribution of energy demand, 106 optimal candidate sites for carbon-neutral villages that can integrate both biomass types were selected. The findings of this study can serve as fundamental scientific data for establishing effective rural energy transition policies in conjunction with rural spatial planning, thereby contributing to the realization of carbon neutrality and the improvement of energy welfare in rural areas.

Keywords: Carbon-neutral village, Forest biomass, Geospatial analysis, Livestock manure, Site suitability analysis

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Introduction

Addressing the climate crisis and achieving carbon neutrality have become global imperatives since the Paris Agreement, prompting countries to transform their energy systems to fulfill their Nationally Determined Contributions (NDCs) [1]. Among various strategies, distributed energy systems utilizing local resources are increasingly recognized as practical alternatives to centralized, fossil-fuel-based energy supply [2]. Rural areas, in particular, hold significant potential to serve as key actors in this transition due to their abundance of organic resources and spatial characteristics [3].

European experiences demonstrate the feasibility of rural energy self-sufficiency. Germany's Bioenergy Villages, such as Jühnde, have realized electricity and heat autonomy through combined heat and power (CHP) systems fueled by agricultural by-products and forest resources. Austria's Güssing successfully reduced fossil fuel dependence by establishing forest-based district heating, simultaneously revitalizing the local economy. Denmark is promoting a nationwide transition to biomethane by expanding livestock manure-based biogas plants, with the ambitious goal of replacing the national gas grid by 2040 [4].

South Korea has committed to reducing greenhouse gas emissions by 40% from 2018 levels by 2030 and to achieving carbon neutrality by 2050 [5]. While industrial and power generation sectors remain central to this effort, rural areas—covering a large portion of the national territory—must also undergo fundamental transformation. Many rural households rely heavily on fossil fuels such as kerosene or LPG due to low city gas supply rates, leading to high energy costs and carbon emissions [6]. Consequently, converting locally available resources, particularly livestock manure and unused forest biomass, into energy offers a promising pathway to enhance rural energy welfare and contribute to national climate goals [7].

However, renewable energy policies in rural Korea have been dominated by solar photovoltaics, which face social acceptance issues, landscape conflicts, and profit-sharing disputes [8]. In contrast, livestock manure and forest biomass represent underutilized but sustainable resources with high potential for circular energy systems. Recent policy changes—including the enactment of the Carbon Neutrality Framework Act (2021), the revision of the Urban Gas Business Act (2024), and the enforcement of the Rural Space Planning Act (2024)—provide institutional support for integrating biomass into regional energy strategies [9].

Despite this potential, previous biomass projects in Korea often failed due to unstable resource supply, lack of economic feasibility, and poor site selection [10]. International studies also reveal limitations, such as reliance on single biomass sources or neglect of demand-side considerations [11,12]. Therefore, a more comprehensive scientific approach is needed that accounts for the spatial distribution of resources, energy demand, infrastructure, and topography to identify feasible sites for biomass-based carbon-neutral villages [13].

The present study aims to overcome these limitations by: (1) analyzing the spatial distribution of livestock manure and forest biomass as dual energy sources; (2) developing a composite index to evaluate the clustering of livestock farms; (3) integrating resource availability with household energy demand to identify suitable sites; and (4) presenting a replicable geospatial methodology that supports national and local policies for rural energy transition.

Results and Discussion

Current status of heating energy use in rural areas

The analysis of monthly energy consumption by rural households (excluding metropolitan cities) showed a pattern of sharp increases in kerosene consumption during the winter season (October-February), when heating demand is concentrated (Fig. 1). This reflects the reality of rural households with low city gas supply rates. As of 2023, the national city gas supply rate reached 83.9%, but in county-level areas such as Sancheong-gun, Gyeongnam (8.8%) and Uiseong-gun, Gyeongbuk (9.1%), the supply rate was remarkably low, showing a clear energy infrastructure gap between urban and rural areas.

In fact, 25.1% of rural households use kerosene for heating, a significantly higher figure compared to urban households (3.9%). A comparison of fuel prices per unit calorific value shows that kerosene and LPG are approximately 2.2 times and 1.7 times more expensive than city gas, respectively, acting as a primary factor aggravating the heating cost burden for rural households (Table 1). Furthermore, the greenhouse gas emission factors by energy source were highest for electricity (132.8 tCO_2 eq/TJ), followed by kerosene (71.9 tCO_2 eq/TJ), LPG (64.5 tCO_2 eq/TJ), and city gas (56.1 tCO_2 eq/TJ). This suggests that the introduction of a biomass-based district heating system, which can reduce fossil fuel dependency and supply affordable heating energy, is critically needed to improve rural energy welfare and reduce carbon emissions.

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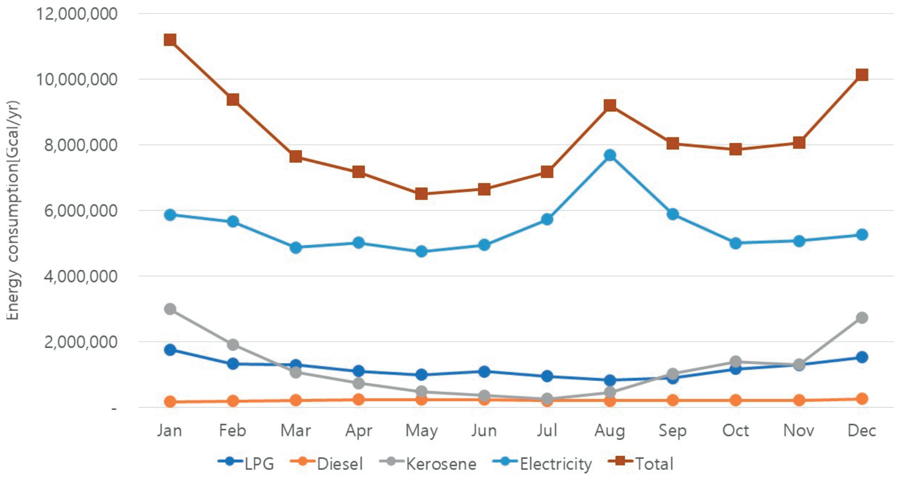

Fig. 1. Monthly energy consumption by fuel type in rural areas (excluding metropolitan cities).

Table 1. Comparison of fuel prices per unit of calorific value

Category	LNG (City gas)	LPG (Cylinder)	Kerosene	LPG (Piped)
Consumer price (KRW)	813.07 /m^3	2,558.17 /kg	1,527.24 /L	1,596.63 /kg
Gross calorific value (MJ/unit)	43.10	103.79	36.70	103.79
Price per MJ (KRW)	18.86	50.76	41.61	31.68
Ratio to city gas	100%	269.1%	220.6%	167.9%

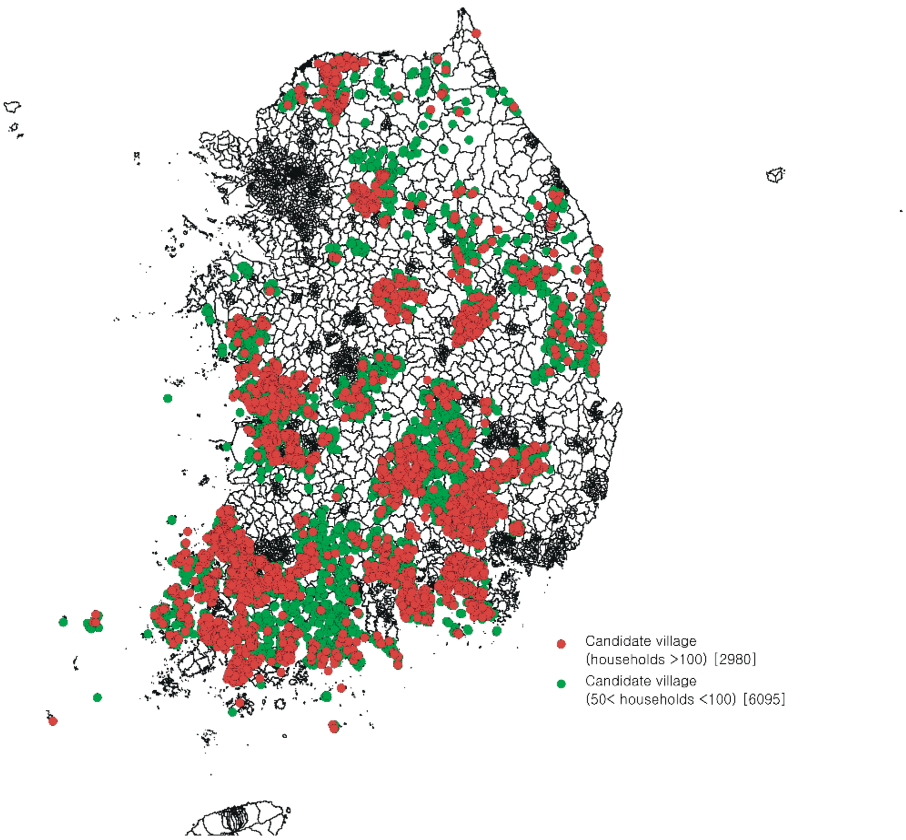

Fig. 2. Distribution of candidate villages suitable for district heating systems.

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Results of selecting villages suitable for heat supply network

A total of 9,075 'villages suitable for heat supply network construction' were identified nationwide, defined as areas without city gas supply where 50 or more households are concentrated within a 500m radius of the village center. Among these, 2,980 villages had 100 or more households, and 6,095 villages had a scale of 50-100 households, confirming the existence of a substantial number of villages with sufficient density to be targets for biomass heat supply projects (Fig. 2). By province, Jeollanam-do (2,966 sites) and Gyeongsangnam-do (2,016 sites) had the highest distribution of candidate villages, while Gangwon Special Self-Governing Province (318 sites), which has many mountainous areas and dispersed housing, had relatively fewer (Table 2). This highlights important spatial characteristics that must be considered when establishing customized regional energy self-sufficiency village dissemination strategies in the future.

Results of livestock manure spatial distribution and clustering analysis

For the stable supply of raw materials and high methane production efficiency from livestock manure, it is important to

Table 2. Number of candidate villages for district heating systems by province and city/county

Province	City/county	No. of villages	Province	City/county	No. of villages	Province	City/county	No. of villages
Total		9075	Jeolla nam-do	Hwasun-gun	175	Gyeongsang nam-do	Namhae-gun	182
Gyeonggi-do	Icheon-si	7		Boseong-gun	72		Goseong-gun	224
	Anseong-si	36		Jangheung-gun	139		Hadong-gun	200
	Yeoju-si	95		Gangjin-gun	73		Sancheong-gun	5
	Yeoncheon-gun	28		Haenam-gun	396		Hamyang-gun	212
	Gapyeong-gun	15		Yeongam-gun	176		Geochang-gun	253
	Yangpyeong-gun	110		Muan-gun	135		Hapcheon-gun	163
	Pocheon-si	109		Hampyeong-gun	257		Subtotal	2016
	Subtotal	400		Yeonggwang-gun	251	Gangwon-do	Wonju-si	18
Chungcheong buk-do	Okcheon-gun	103		Wando-gun	6		Samcheok-si	44
	Goesan-gun	246		Sinan-gun	270		Hongcheon-gun	22
	Danyang-gun	54		Subtotal	2966		Yeongwol-gun	41
	Subtotal	403	Gyeongsang buk-do	Gimcheon-si	136		Pyeongchang-gun	10
Chungcheong nam-do	Boryeong-si	63		Gyeongsan-si	47		Cheorwon-gun	100
	Nonsan-si	4		Cheongsong-gun	66		Hwacheon-gun	20
	Dangjin-si	33		Yeongyang-gun	47		Yanggu-gun	26
	Geumsan-gun	155		Yeongdeok-gun	107		Inje-gun	25
	Buyeo-gun	276		Cheongdo-gun	175		Goseong-gun	2
	Seocheon-gun	162		Goryeong-gun	70		Yangyang-gun	10
	Hongseong-gun	138		Seongju-gun	151		Subtotal	318
	Taean-gun	15		Chilgok-gun	14	Jeonbuk-do	Gunsan-si	201
	Subtotal	846		Yecheon-gun	268		Iksan-si	140
Jeolla nam-do	Yeosu-si	62		Bonghwa-gun	105		Jeongeup/namwon	2
	Suncheon-si	82		Uljin-gun	78		Gimje-si	382
	Naju-si	348		Subtotal	1264		Wanju-gun	75
	Gwangyang-si	120	Gyeongsang nam-do	Tongyeong-si	124		Jinan/muju	5
	Damyang-gun	31		Gimhae-si	45		Imsil-gun	10
	Gokseong-gun	73		Uiryeong-gun	216		Sunchang-gun	10
	Gurye-gun	64		Haman-gun	139		Buan-gun	37
	Goheung-gun	236		Changnyeong-gun	253		Subtotal	862

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install biogas systems in areas where livestock farms are concentrated (Fig. 3, Fig. 4). As a result of analyzing the spatial distribution characteristics of livestock farms at the Eup/Myeon level using ANNI and CNI in this study (Fig. 5), suitable sites for biogas plant construction could be classified into three types (Table 3).

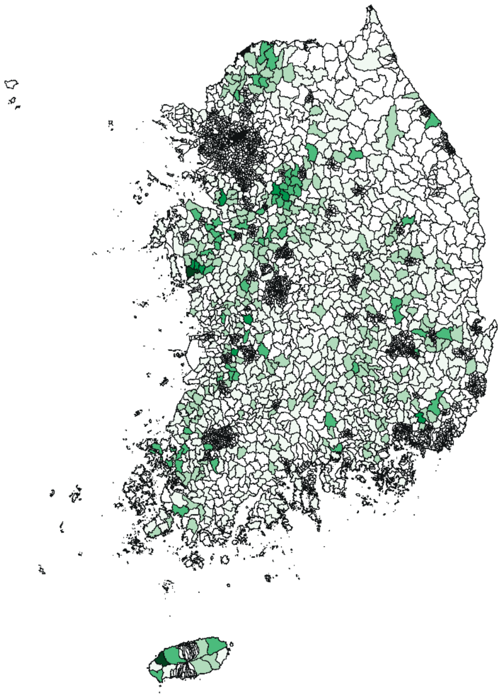

Fig. 3. Total livestock headcount by Eup/Myeon.

Fig. 4 Livestock density by Eup/Myeon.

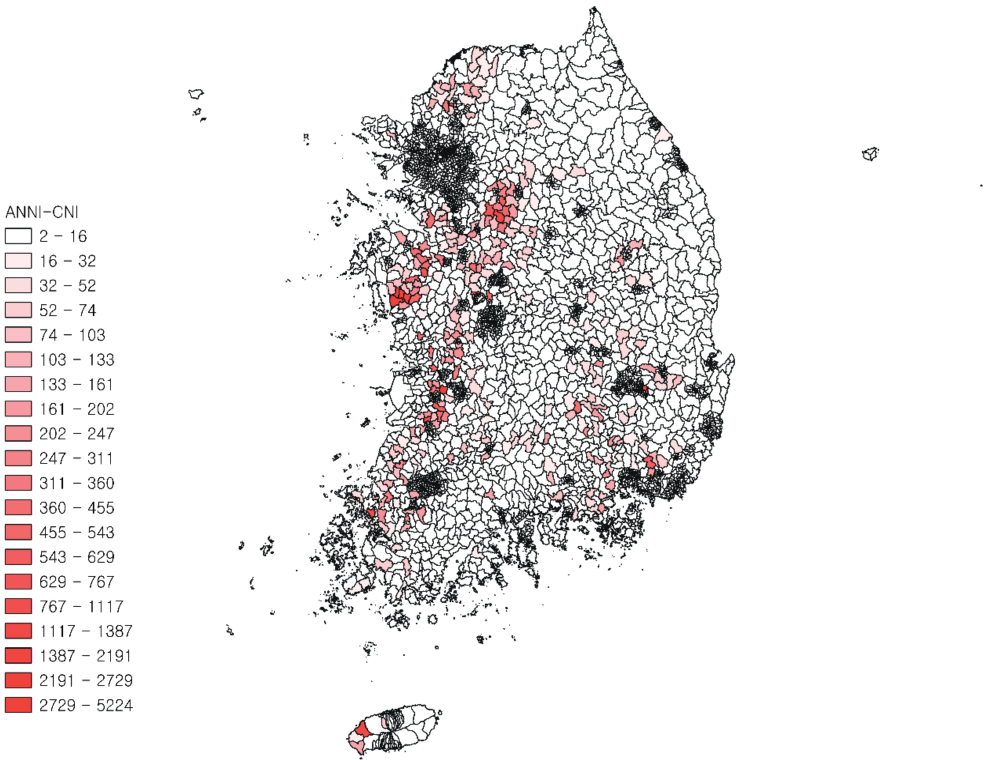

Fig. 5. ANNI-CNI analysis results.

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Table 3. Classification of eup/myeon by suitability for biogas plant construction

Classification	Eup/myeon	No. of farms	Total headcount	Farm density (farms/km^2)	ANNI (R)
Priority for plant construction	Hallim-eup	100	246,765	1.09	0.46
	Cheonbuk-myeon	60	221,220	0.93	0.86
	Eunha-myeon	43	141,601	1.40	0.81
	Baegam-myeon	35	117,696	0.53	0.79
	Iljuk-myeon	41	117,613	0.74	0.88
	Yongji-myeon	38	114,309	1.09	0.70
	Jangan-myeon	30	111,981	0.44	0.59
	Hallim-myeon	39	98,060	0.66	0.55
	Gwangcheon-eup	36	92,533	1.03	0.55
	Gyeolseong-myeon	26	78,305	0.89	0.93
Large scale but dispersed	Cheonggye-myeon	10	68,800	0.15	1.41
	Janggok-myeon	22	63,305	0.40	1.05
	Unnam-myeon	22	60,615	0.63	1.02
	Godae-myeon	9	57,730	0.14	1.22
	Bubal-eup	8	56,350	0.19	1.19
Small scale and dispersed	Ian-myeon	3	3,300	0.06	2.86
	Bongsan-myeon	3	4,090	0.04	2.54
	Hogye-myeon	3	4,250	0.06	3.13
	Songhak-myeon	3	4,340	0.04	3.25
	Gucheon-myeon	3	4,450	0.07	3.09

This categorization also aligns with current policy directions under the Rural Spatial Planning Act, which requires local governments to designate functional zones based on regional characteristics. Areas with concentrated livestock activities may be designated as livestock zones, while dispersed small-scale farms are often considered for relocation or gradual reduction. Therefore, the inclusion of ‘scaling-down advocated areas’ in this study provides policy-relevant spatial information for regions where such small and dispersed farms are expected to decline over time.

First, ‘Priority areas for plant construction’ are regions with high headcounts and farm density, and a clustered distribution (ANNI < 1). Areas like Hallim-eup and Cheonbuk-myeon, with total headcounts exceeding 100,000 and concentrated farms, were evaluated as having the highest suitability for plant siting due to high efficiency in manure collection/transport and guaranteed stability of raw material supply.

Second, ‘Consolidation required areas’ are regions with large total headcounts (over 50,000) but dispersed farms (ANNI > 1). Areas like Cheonggye-myeon and Janggok-myeon have high resource potential, but manure collection costs would be high, resulting in low economic feasibility at present. Therefore, they need to be converted into candidate sites in conjunction with mid- to long-term livestock farm consolidation policies.

Third, ‘Scaling-down advocated areas’ are regions where both the number of farms and headcounts are small, and the distribution is dispersed. In these areas, it is more reasonable to gradually reduce the scale of livestock operations and implement environmental load reduction policies rather than constructing biogas plants.

Decision-making models using geographic information have advanced with the development of machine computation technology. In the Mediterranean region, efforts have been made to develop and evaluate approaches to biogas potential to support the bioenergy industry. An Analytical Hierarchy Process (AHP) combined with GIS-based analysis, utilizing spatial relationships (i.e., proximity analysis) and integrating time-series data of continuous and discrete data, has been reported. This involved developing a spatial information system to support biogas planning, analyzing biogas feedstock from various sources, and generating

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scenarios to identify territorial clusters suitable for biogas [14]. This method has also been applied in southern Finland, where a GIS-based methodology was used that included optimizing biomass transport considering the existing road network and spatially diverse biomass sources. Kernel Density (KD) maps were calculated to identify areas with high biomass concentrations. The reported study suggested that this could be used to identify the most suitable locations for biogas plants by providing tools for transport routes and distances [14]. In contrast, the methodology in this study provides a more nuanced spatial analysis by incorporating the Average Nearest Neighbor Index to quantify clustering, rather than relying solely on density maps.

Results of forest biomass availability and resource center site review

It has been reported that forest biomass will contribute to a carbon-neutral society at the national level in the near future. Low-value forest residues left in forests are called 'unused forest biomass'. The estimated raw material amount in 2050, the sustainably collectible amount, and the amount usable for wood pellets are estimated at 6,877, 4,814, and 3,370 thousand tons, respectively, with a maximum NDC contribution rate estimated at 0.64% [15]. However, as of 2024, the domestic wood pellet self-sufficiency rate is only 18.1%, making the utilization of unused forest biomass crucial for a stable raw material supply.

An analysis of the 50km supply radius of the five currently operating resource centers (Jangheung, Paju, Yesan, Namwon, Seongju) revealed that the production volume of each center alone is insufficient to meet the potential demand within its catchment area, based on the case of Dambau Village in Goesan (approx. 700 tons/year per 60 households) (Table 4). For example, the Jangheung center has 1,447 candidate villages within its supply zone, but its production can only cover 100 villages.

Therefore, establishing new resource centers is essential to supply stable raw materials to the gap areas excluded from the supply networks of the five existing centers. It is proposed that nine new centers be established in regions with abundant growing stock: Gangwon region (Hwacheon, Wonju, Yeongwol), Chungcheong region (Okcheon), Gyeongbuk region (Mungyeong, Yeongyang), Honam region (Iksan, Yeonggwang), and Gyeongnam region (Jinju) (Fig. 6). If these nine new centers are established, most of the 9,075 candidate villages nationwide would be included within a 50km supply radius, thereby establishing a stable raw material supply system (Table 5).

Table 4. Number of candidate villages within the 50km radius of existing resource centers

Center	Production (thousand tons/year)	No. of candidate villages within 50 km	No. of serviceable villages†
Jangheung-gun	70	1447	100
Paju-si	30	208	42
Yesan-gun	25	349	35
Namwon-si	40	692	57
Seongju-gun	40	866	57

† Based on the case of Dambau Maeul in Goesan (approx. 700 tons/year per 60 households)

Table 5. Estimated number of candidate villages and required production capacity for proposed new resource centers

Proposed new center region	No. of candidate villages within 50 km	Required production (thousand tons/year)
Hwacheon	227	159
Wonju	303	212
Yeongwol	327	229
Mungyeong	580	406
Yeongyang	367	257
Okcheon	355	249
Iksan	1410	987
Yeonggwang	1522	1065
Jinju	1293	905

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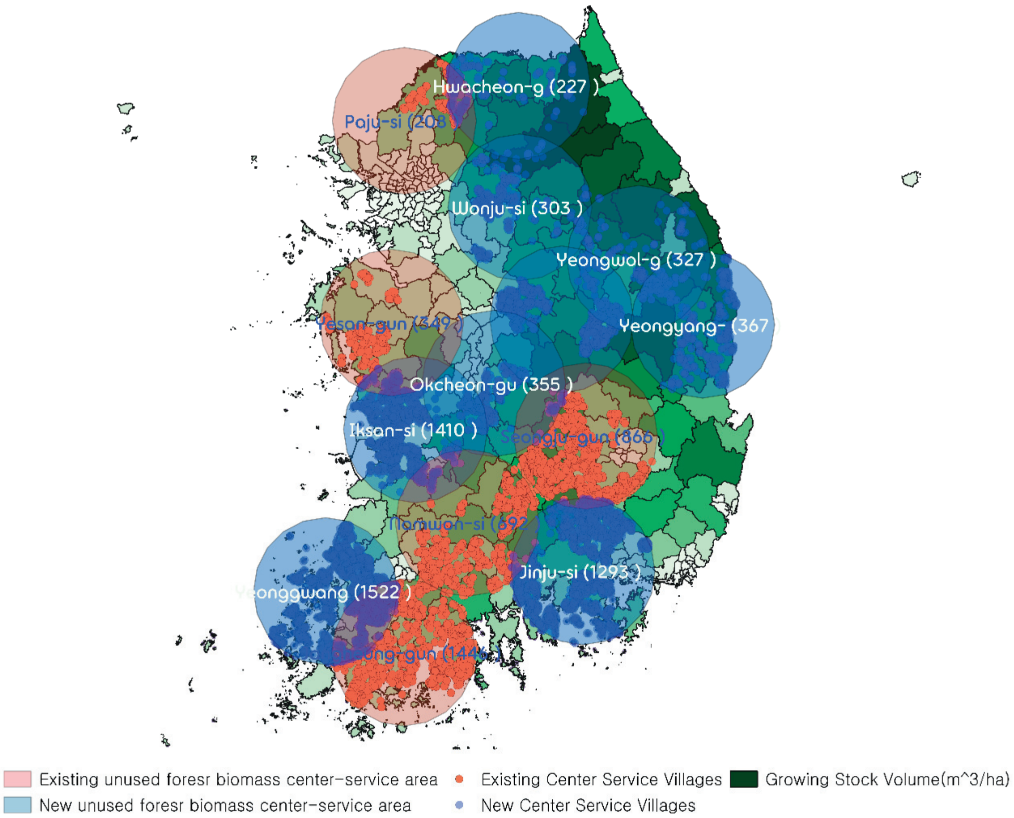

Fig. 6. Existing and proposed new resource centers and their supply coverage.

Results of site selection for carbon-neutral villages

The optimal sites for integrated carbon-neutral villages were derived by spatially overlaying three conditions: energy demand ('villages suitable for heat supply network construction'), livestock manure supply ('valorization priority areas'), and forest biomass supply ('resource center supply zones') (Fig. 7).

To clarify the stepwise filtering process, the number of villages remaining at each stage was explicitly examined. First, a total of 9,075 villages were identified nationwide as suitable for heat supply network construction. Among these, 3,562 villages were located within the 50 km supply coverage zones of the existing and proposed forest biomass resource centers, indicating that they can secure a stable supply of unused forest biomass. By further intersecting these 3,562 villages with the livestock manure valorization priority areas (ANNI < 1 and CNI > 50), a total of 106 optimal candidate villages were ultimately selected.

As a result of the analysis, a total of 106 villages that satisfy all three conditions were selected within the supply zones of the five currently operating resource centers (Fig. 8). These locations fall within the livestock manure valorization priority areas (ANNI<1 and CNI>50), are capable of stable supply of unused forest biomass, and possess the minimum energy demand density for district heating. Therefore, these 106 villages can be considered top-priority candidate sites for pilot projects for carbon-neutral villages that integrally utilize livestock manure and forest resources.

In the Ankara region of Turkey, a similar stepped approach and criteria were applied to determine potential biomass-based villages, and multi-criteria weights were assigned using the Analytical Network Process (ANP) method. It should be noted that this case was a site evaluation study and not an implemented pilot project. Therefore, it was referenced in this study for its methodological relevance rather than as evidence of an operational demonstration. [16].

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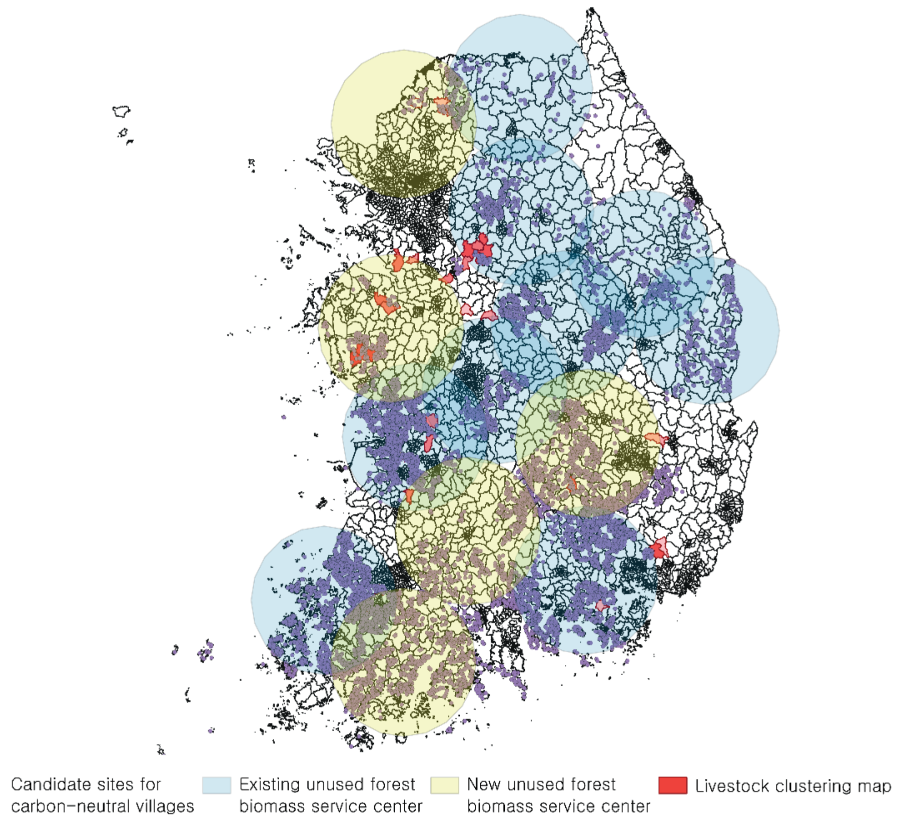

Fig. 7. Spatial distribution of candidate villages and priority zones for biomass and livestock manure utilization centers.

Fig. 8. Mapping potential candidate sites for carbon-neutral villages.

Conclusion

This study developed a geospatial framework to utilize local organic resources—livestock manure and forest biomass—through spatial information analysis to achieve energy self-sufficiency and carbon neutrality goals in rural areas. The research results showed that there are 9,075 potential villages nationwide in areas without city gas supply that could introduce biomass-based district heating.

In particular, by quantitatively analyzing the density and distribution patterns of livestock farms, this study presented priorities for biogas plant siting. It also confirmed that the expansion of existing resource centers is essential for the stable supply of unused forest biomass and proposed nine new center locations.

By synthesizing these analyses, 106 optimal candidate sites for carbon-neutral villages that can simultaneously utilize both livestock manure and forest resources supply chains were derived. This holds significant policy implications, presenting specific target sites that could transform rural areas — previously marginalized from the centralized energy system - into hubs for distributed energy production. The findings of this study can be utilized as a scientific basis in the practical policy-making processes of local governments, such as the designation of 'Energy Districts' under the 「Rural Space Planning Act」, and will contribute to increasing the efficiency of strategic resource allocation and investment. In conclusion, this study sought to contribute to sustainable rural development and the national energy transition by presenting a concrete roadmap for realizing rural carbon neutrality through data-based spatial analysis.

This study has several limitations, which in turn suggest directions for future research. As this study focused on physical location conditions and resource potential, further review is necessary regarding the economic feasibility (investment/operation costs, carbon reduction value assessment), social acceptability (resident acceptance), environmental impacts (air, water, soil quality), and administrative procedures for actual project implementation for individual candidate sites. Future research should focus on developing sustainable biomass energy business models and apply them in the field by conducting detailed economic feasibility analyses and social/environmental impact assessments for the derived candidate sites.

In summary, this study presented strategic candidate sites for rural carbon-neutral villages through an integrated analysis of key resources—livestock manure and forest biomass—using spatial information. However, for actual commercialization, complementary research on economic feasibility, social acceptability, and operational risks, supported by an appropriate institutional framework, must be pursued concurrently

Materials and Methods

Data collection and analysis procedure

To quantitatively analyze the feasibility of establishing carbon-neutral villages based on livestock manure and forest biomass using geospatial information, this study collected various public data as shown in Table 6. The temporal scope of the data used in this study is the year 2022. The open-source GIS program QGIS (ver. 3.34.15 Prizren) was used for geospatial information analysis. Vector and raster-based spatial analysis tools were employed to perform operations such as Buffer, Intersect, filtering, and spatial statistics (Average Nearest Neighbor, Kernel Density). All spatial data were standardized to the EPSG:5179 (KGD2002 / Unified CS) coordinate system to ensure analytical accuracy.

The analysis procedure was as follows. First, villages suitable for the construction of a biomass-based heat supply network were extracted from areas not supplied with city gas. Second, the distribution of livestock manure and forest resources within rural areas was quantitatively analyzed based on geospatial information. Third, the optimal sites for carbon-neutral village establishment were derived by integrating the supply range of unused forest biomass resource centers and the areas with potential for livestock manure valorization.

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Table 6. Data used for the analysis

Category	Data	Source	Purpose
Rural household energy	Survey on Farm Household Energy Consumption	Korea Rural Economic Institute	Analysis of energy consumption by source in rural areas
Consumption analysis	Domestic Petroleum Statistics by Product and Industry	Petronet	
	Average Household Electricity Usage by Region	KEPCO Power Data Open System	
Forest statistics	Growing Stock, Forest Area	Korea Forest Service, KOSIS	Analysis of forest resources distribution and supply potential
Center information	Location and Production of Unused Forest Biomass Resource Centers	Korea Forest Service (KFS)	Setting feasible fuel supply zones
Livestock information	Livestock Headcount by Parcel	Animal and Plant Quarantine Agency	Analysis of livestock manure generation and density
Geospatial information	Administrative Districts, DEM (Digital Elevation Model), Community Center Locations	VWorld	Identification of villages for heat supply, terrain analysis
Energy information	City Gas Supply Status	Korea City Gas Association, etc.	Filtering areas not supplied with city gas
Population/ Household	Number of Houses (Road Name Address Map)	Address-based Industry Support System	Determining the scale of villages for heat supply

Analysis of household energy consumption by source in rural areas

Energy consumption by source was calculated for households nationwide, excluding metropolitan areas where city gas is supplied. Monthly petroleum consumption data by city/county (*si/gun/gu*) provided by Petronet and monthly household electricity usage by city/county from the Korea Electric Power Corporation (KEPCO) were converted into energy units. The conversion standards were based on the [Annex Table] of the 「Enforcement Rule of the Energy Act」.

Selection of villages suitable for heat supply network construction

Selection criteria and procedure

To secure the economic feasibility of a biomass-based district heating system, it is essential to select target villages where a sufficient scale of energy demand is spatially concentrated. In this study, villages suitable for heat supply network construction were systematically selected through the following four-step procedure.

Extraction of areas not supplied with city gas

First, to identify regions highly dependent on fossil-fuel-based heating energy, *eup* and *myeon* (township and village) areas not supplied with city gas were extracted. Using the city gas supply status data (as of 2022) from the Korea City Gas Association and pipeline network distribution data provided by each city and province, the city gas supply status was determined at the administrative district (*eup/myeon*) level. Rural areas with low city gas supply rates primarily use kerosene or LPG as heating fuel, resulting in high energy cost burdens and significant greenhouse gas emissions.

Analysis of household density at the village level

Construction of housing geospatial database

Using the 'Road Name Address Electronic Map' data (provided by the Ministry of the Interior and Safety, as of 2022), the location information of detached houses nationwide was constructed as a GIS database. This data includes building classification information by use, enabling the accurate identification of household distribution in rural villages by extracting detached houses.

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Setting village centroids and calculating household counts

The location coordinates of community centers (*maeul-hoegwan*) provided by VWorld were set as the village centroids. In most rural villages, the community center is located in the center of the residential cluster and functions as a hub for resident activities, making it suitable as an origin point for a district heating system.

Using the Buffer function in QGIS, a circular area with a 500m radius was generated around each community center, and the number of detached houses located within this area was calculated. The 500m radius criterion is based on the following two rationales. First, the construction cost of district heating pipelines increases in proportion to distance, and economic feasibility sharply declines beyond 500m due to increased heat loss and pump power requirements [17]. Second, considering that the average spatial extent of domestic rural villages is 300–600m [17], a 500m radius is deemed an appropriate distance that encompasses most of the village while maintaining heat supply efficiency.

Establishment of minimum household count criterion

The household count criterion for securing the minimum economic feasibility of the heat supply network was set at 50 households. This was derived from the analysis of the following domestic and international cases:

- **German Bioenergy Village Cases:** An analysis of Germany's Bioenergy Villages (*Bioenergiedörfer*) program reported that the minimum demand scale required to secure the economic feasibility of a district heating system is 40–60 households [3].
- **Domestic Precedent Case:** Dambau Village in Goesan (60 households) stably operates a small-scale combined heat and power (CHP) system (100kW class), consuming approximately 700 tons of wood pellets annually [17]. This demonstrates that operational economic feasibility is secured at a scale of 50 households or more.
- **Economic Feasibility Analysis:** In areas with fewer than 50 households, the per-household facility investment cost (for pipelines, heat exchangers, etc.) increases excessively, making it difficult to secure economic feasibility as the payback period exceeds 20 years.

Therefore, this study designated villages with 50 or more households concentrated within a 500m radius of the centroid as 'basic heat supply network candidate sites'.

Topographical condition assessment and final candidate site selection

When installing a district heating pipeline network, topographical conditions have a significant impact on construction costs and heat supply efficiency. In this study, the elevation deviation among houses within the basic candidate sites was analyzed using a Digital Elevation Model (DEM; 5m × 5m resolution).

Calculation of average elevation deviation

For each basic candidate site, the elevation values of all houses located within the 500m radius were extracted, and the difference between the maximum and minimum elevation was defined as the 'average elevation deviation'. This indicator represents the expected elevation range to be covered when installing the heat supply pipeline network for all houses within the village.

Establishment of elevation difference criterion

Areas with an 'average elevation deviation' of 5m or less were selected as final candidate sites for heat supply network construction. This criterion is based on the following technical and economic rationales:

- **Construction Difficulty:** A larger elevation difference increases the ground excavation depth during pipe installation and incurs additional costs associated with slope construction.
- **Increased Heat Loss:** In areas with large elevation differences, the pipeline length increases and heat loss is greater, leading to reduced heat supply efficiency.
- **Basis in Prior Research:** A previous study on district heating systems reported that heat supply efficiency decreases by

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20% or more in areas with a slope greater than 10% (approx. 5.7m/50m) [17]. When converted to a 500m radius standard, this corresponds to an elevation difference of approximately 5m.

• **Increased Pump Power:** A larger elevation difference increases the pump power consumption required for circulating the heat medium, leading to higher operating costs.

Finally, villages that satisfied all three conditions (1) location in an area not supplied with city gas, (2) concentration of 50 or more households within a 500m radius, and (3) an 'average elevation deviation' of 5m or less—were selected as candidate sites suitable for biomass-based heat supply network construction.

Livestock manure spatial distribution and clustering analysis

Construction of livestock farm geospatial database and calculation of basic statistics

To select optimal sites for biogas plants for the efficient valorization of livestock manure, the spatial distribution characteristics of livestock farms at the nationwide *eup* and *myeon* (township and village) levels were analyzed. A database on the status of livestock farms by *eup/myeon* was constructed by performing a spatial join in the QGIS program, using livestock farm coordinate data (as of 2022) provided by the Animal and Plant Quarantine Agency (APQA) and administrative boundary vector data.

For each *eup* and *myeon*, the number of farms (No.), total headcount (head), farm density (farms/km^2), and livestock density (head/km^2) were calculated. Based on these metrics, the potential manure generation and spatial distribution patterns for each region were quantitatively evaluated.

Spatial concentration analysis using the Average Nearest Neighbor Index (ANNI)

To quantify the degree of spatial clustering of livestock farms, the Average Nearest Neighbor Index (ANNI) was utilized [18]. ANNI is defined as the ratio (R) of the observed mean nearest neighbor distance (D_{obs}) to the expected mean distance (D_{exo}) assuming a random distribution. An R-value less than 1 indicates a clustered distribution, R ≈ 1 indicates a random distribution, and R > 1 indicates a dispersed distribution. In this study, the ANNI R-value was used as a key indicator for evaluating the efficiency of manure collection and transport. The more spatially clustered the farms (R < 1), the shorter the travel distance for collection vehicles, thus reducing logistics costs. Conversely, a dispersed distribution (R > 1) decreases collection efficiency and reduces the economic viability of biogas plant operation.

Development and calculation of the Concentration Index (CNI)

To comprehensively evaluate farm spatial distribution characteristics and livestock scale, this study newly developed a Concentration Index (CNI). The CNI is calculated by multiplying the Farm Dispersion Index (FDI), Farm Density (FD), and Pig Density (PD), and it is used as a composite indicator to comprehensively evaluate the suitability for biogas plant construction.

$$CNI = FDI \times FD \times PD$$

Where,

- FDI: An index of farm spatial dispersion; in this study, the ANNI R-value was used as a proxy for FDI.
- FD: Farm Density (farms/km^2)
- PD: Pig Density (head/km^2)

(i) Farm Dispersion Index (FDI)

In this study, the FDI was represented directly by the ANNI R-value without mathematical transformation. The purpose of including the R-value in the CNI was not to amplify its magnitude as a standalone factor but to retain the directional meaning of spatial distribution as a moderating component within the composite index. An R-value less than 1 indicates a clustered distribution of livestock farms, which is generally favorable for manure collection due to shorter travel distances. Conversely,

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an R-value greater than 1 reflects dispersed farm patterns that increase transport costs and reduce operational efficiency.

By incorporating the R-value directly into the CNI formula, the index captures relative differences in spatial distribution among regions while allowing FD and PD—the primary determinants of resource scale—to play the dominant role in driving the magnitude of the CNI. This design ensures that spatial clustering is accounted for qualitatively within the composite index without disproportionately influencing the overall numerical score, thereby aligning the index with the empirical characteristics observed in domestic biogas plant operations.

(ii) Farm Density (FD)

FD refers to the number of livestock farms per unit area (km^2). A higher farm density enables the realization of economies of scale when establishing manure collection infrastructure. An analysis of operational cases of domestic biogas plants indicated that a stable raw material supply and an efficient collection system are feasible in regions where the farm density is 0.5 farms/km^2 or higher. Therefore, FD ≥ 0.5 farms/km^2 was set as the threshold value for plant site evaluation in this study.

(iii) Pig Density (PD)

PD refers to the number of pigs raised per unit area (km^2) and is directly linked to the methane production potential and energy generation scale of the biogas plant. Considering the characteristics of domestic pig manure, the annual manure generation per pig is approximately 2.5 tons, and the potential methane gas production from this via anaerobic digestion is estimated to be about 25 m^3 [12]. A higher livestock density ensures the stability of the plant's raw material supply and increases energy production, thereby improving economic feasibility.

CNI-based regional classification system and threshold setting

Based on the CNI values, all *eup* and *myeon* regions nationwide were classified into three types according to their suitability for biogas plant construction (Table 2). The thresholds were derived by analyzing the farm distribution characteristics and operational performance of successful domestic biogas plant cases (e.g., Gimje-si, Yesan-gun) and reflect the minimum daily processing capacity (50 tons or more) required to ensure plant economic viability.

An examination of the nationwide CNI distribution revealed clear differentiation among the three categories. Priority areas for plant construction (CNI > 50) represented only 2–3% of all eup/myeon, indicating rare but highly favorable conditions where clustered farm locations and large livestock populations coincide. Areas requiring consolidation (20 < CNI ≤ 50) accounted for roughly 15–20% of regions and possessed sufficient manure resources but exhibited dispersed farm patterns, leading to substantially higher collection costs. In contrast, areas with CNI < 20 comprised more than 80% of all units, reflecting low livestock scales and spatially dispersed farms that are generally unsuitable for centralized biogas plant development. These findings correspond well with the operational characteristics of existing domestic biogas plants, supporting the validity of the CNI-based classification system proposed in this study.

(i) Priority areas for plant construction (CNI > 50)

These are regions where the CNI value exceeds 50, combined with an ANNI < 1.0 and a total livestock headcount of 100,000 or more. These areas are characterized by spatially clustered farms and large-scale livestock operations. They are assessed as top-priority candidate sites where biogas plant construction is immediately feasible due to high manure collection efficiency and a stable raw material supply.

(ii) Areas requiring farm consolidation (20 < CNI ≤ 50)

These are regions with an ANNI > 1.0 or a headcount between 50,000 and 100,000, where farms are dispersed. Although the raw material supply potential is sufficient, achieving economic feasibility under current conditions is challenging due to ex-

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cessive manure collection costs. Therefore, plant construction should be considered in the mid- to long-term, in conjunction with farm consolidation policies (e.g., establishing livestock complexes, constructing joint treatment facilities).

(iii) Areas advocating for livestock scale reduction (CNI < 20)

These are regions with a CNI value below 20. They are characterized by a low number of farms, small headcounts, and a spatially dispersed distribution. It is difficult to secure economic feasibility for a biogas plant in these areas; thus, it is more rational to consider gradual livestock scale reduction and small-scale, decentralized treatment methods (e.g., on-farm composting) to reduce the environmental load.

This classification system provides a methodological framework for objectively and systematically evaluating biogas plant site suitability by integrating quantitative indices (CNI, ANNI) and livestock scale.

Analysis of forest biomass availability and review of resource center sites

The necessity of expanding unused forest biomass resource centers was examined to ensure a stable biomass supply for carbon-neutral villages. A stable raw material supply radius for a forest energy self-reliant village was set at 50 km, and the supply zones of the five currently operational centers were analyzed. Furthermore, for the gap areas outside the supply networks of the existing centers, optimal locations for new resource centers were derived by considering the growing stock volume.

Site selection for carbon-neutral villages

To derive optimal sites for carbon-neutral villages that can integrally utilize both livestock manure and forest biomass resources, a spatial overlay analysis was performed using the QGIS program. Three spatial data layers were used as inputs: (1) villages suitable for heat supply network construction, (2) livestock manure valorization priority areas, and (3) forest biomass supply zones based on the 50 km coverage of existing and proposed resource centers.

To improve transparency of the selection procedure, the site selection was carried out using a stepwise filtering process. First, 9,075 villages were identified nationwide as suitable for heat supply network construction based on household density (≥50 households within a 500 m radius), elevation constraints (average elevation deviation ≤5 m), and exclusion of city-gas-supplied areas. Second, these 9,075 villages were intersected with the 50 km supply coverage zones of existing and newly proposed forest biomass resource centers, resulting in 3,562 villages where unused forest biomass can be supplied stably. Third, the 3,562 villages were intersected with livestock manure valorization priority areas defined by CNI > 50 and ANNI < 1. Through this sequential overlay analysis, a total of 106 final candidate villages were identified.

The final selected sites therefore represent areas that concurrently satisfy three essential conditions: sufficient and concentrated heat demand, proximity to forest biomass supply sources, and high potential for livestock manure-based biogas production.

Data Availability: All data are available in the main text or in the Supplementary Information.

Author Contributions: C.E.H. and L.S.H. conceived and designed the research; C.E.H. collected the data and performed the analysis; C.E.H. wrote the first draft of the manuscript; C.E.H., N.J.J., and L.S.H. revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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