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Provincial Biogas Potential: Technical & Economic Assessment of Manure-Based Energy Across Iran

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ABSTRACT

Anaerobic digestion of livestock manure offers a pathway for Iran to mitigate seasonal energy imbalances. During the four- month, thermal power plants' methane consumption rises by an average of 85 Mcm/day (2,650 Mcm/month), peaking at 309 Mcm/day. This study identifies a national biomethane potential of approximately 12.7 Mcm/day from 92.1 Mt of annual collectible manure. If stored and dispatched seasonally, this capacity could offset nearly two months of the incremental peak demand observed in thermal power plants.
Economically, the research advocates for a strategic shift from biogas-to-electricity toward biogas-to-renewable natural gas (RNG) injection. decoupling power-generation infrastructure reduces capital expenditure by 51.52%, boosting the internal rate of return from 9.2% to 29 % and shortening the payback period to four years.
To the best of the authors' knowledge, this research represents the first application of the Livestock Standard Unit Equivalent (LSU_e) framework to Iranian provincial livestock distribution. This methodology yields an estimated 50.6 m3 of biomethane per tonne of fresh manure. Integrating these results with economic screening identifies Mazandaran and Golestan as primary provinces for targeted bioenergy expansion

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INTRODUCTION

The world's reliance on fossil fuels, coupled with rising global energy demand, presents two of the most critical challenges we face today: ensuring long-term energy security and mitigating the catastrophic environmental impacts of climate change (IPCC, 2023). In this context, the role of renewable energy sources has become increasingly important for sustainable energy production. Among these, biogas is a versatile and rapidly expanding option. Biogas not only meets energy needs but also addresses pressing environmental issues, contributing to public health improvement. Biogas systems support waste management by treating organic wastes through anaerobic digestion, reducing pollution impacts and capturing methane for energy use. It plays a crucial role in mitigating greenhouse gas emissions by capturing potent methane (CH_4) that would otherwise escape into the atmosphere (Noorollahi et al., 2015).

Technically, anerobic digestion (AD) converts organic streams (such as manure, residues, and sludge) into biogas and nutrient-rich digestate (Jørgensen & Day, 2009). Upgrading

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biogas to biomethane as a high-purity energy carrier enables direct grid injection, utilization as transportation fuel (Bio-CNG), or high-efficiency combined heat and power (CHP) deployment, effectively transforming waste into a versatile energy asset (Meyer et al., 2018).

Unlike intermittent energy sources such as solar and wind, biogas can be produced continuously, making it a reliable and dispatchable power source (IRENA, 2024). This characteristic enables consistent operation and allows easy and cost-effective storage in large gas tanks for later use. Such storage capabilities are essential for managing the peak energy demand.

While biomethane represents a global opportunity for grid decarbonization, its application is particularly vital for nations heavily dependent on natural gas, such as Iran. Despite accounting for only 1% of the world's population, Iran possesses 17% of global natural gas reserves (the second largest after Russia) yet consumes approximately 6% of the global supply (Esen & Oral, 2016). This disproportionate consumption has led to significant systemic pressure. In 2023, Iran's total natural gas consumption reached 237 Bcm/year (approximately 649 Mcm/day), with the household sectors alone accounting for 131 Bcm/year (323 Mcm/day) (VCM, 2024).

The severity of this dependence is most evident in the power sector, where 83.2% of thermal power plant fuel is supplied by natural gas (SCI, 2025). However, seasonal supply-demand imbalances frequently disrupt this flow. In 2023, gas deficit forced thermal power plants to consume 18 billion liters of expensive liquid fuels (diesel and fuel oil), incurring a staggering economic cost of 9 billion dollars (VCM, 2024). This energy imbalance underscores the urgent need for alternative, storable, and grid-compatible fuels like biomethane to safeguard Iran's energy infrastructure and reduce the multi-billion-dollar burden of liquid fuel substitution.

Global Biogas Landscape and Iran's Strategic Potential

Global biogas potential from major feedstocks is estimated between 10,100 and 14,000 TWh, a resource capable of satisfying up to 22% of global electricity demand (WBA, 2019). Specifically, animal manure is a critical component of this potential, with 12 billion tonnes produced annually, its anaerobic digestion could yield 250-370 Bcm of biomethane, sufficient to meet 4-6% of the world's electricity needs.

Despite this vast capacity, current utilization remains marginal, with global biogas-derived electricity reaching only 85.59 TWh in 2023 (a mere 0.3% of the total global supply (IEA, 2025; IRENA, 2025a)) (Fig. 1). Mirroring this disparity, nations like Iran possess immense biomass resources estimated at 172.3 million tonne annually, where animal manure emerges as the most promising feedstock (Heidari et al., 2019). Nonetheless, even with an extensive livestock sector and diverse climates ensuring a consistent organic supply, Iran's national bioenergy development remains nascent (Rouhollahi et al., 2020).

Literature Review

A critical analysis of extant literature reveals significant discrepancies in livestock census data and the subsequent estimation of bioenergy potential in Iran. Study (Abdoli MA & M., 2014) evaluates a population of 63.4 million small and large livestock, estimating a manure yield of 62.7 Mt with a projected biogas potential of 15,678 thousand cubic meter (approximately 15.68 Mcm). While this report introduces accessibility coefficients for various species manure, it lacks methodological transparency regarding its calculations and entirely overlooks the poultry sector. Furthermore, its estimated biogas yield appears negligible when contrasted with contemporary research.

Study (Asadinejad et al., 2016) reports an annual manure production of 74.9 Mt, with a corresponding biogas potential estimated at 8,668 Mcm. However, this study fails to account for poultry-derived manure and lacks detailed reporting on livestock demographics or the practical collectability of the manure. Study (Manesh et al., 2020) focuses exclusively on the poultry

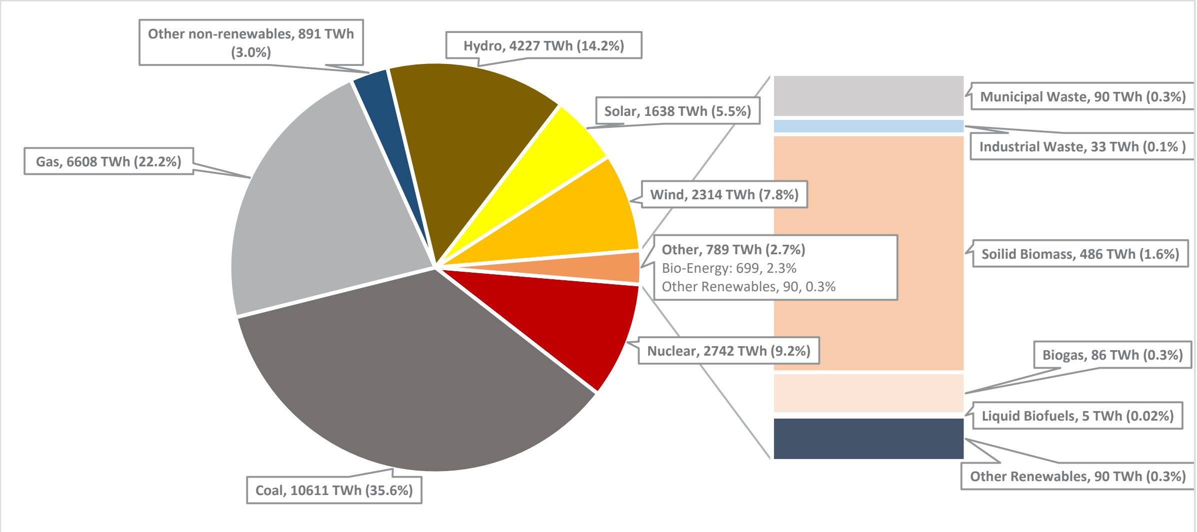

Fig. 1. Breakdown of global electricity supply in 2023 (TWh)(IEA, 2025; IRENA, 2025a; WBA, 2024)

sector, analyzing 274 million chickens, it estimates 1.9 Mt of annual poultry manure, yielding a biogas potential of 525.8 Mcm per year. Finally, Study (Safieddin Ardebili, 2020) adopts a broader scope by investigating livestock and poultry together. It estimates a total available manure mass of 108.4 Mt annually, with a potential biogas output of 11,523 Mcm. This report determines manure yield based on a percentage of live weight and utilizes only three generalized conversion coefficients for its estimations.

Research Gap, Objectives, and Innovation

The observed dispersion in existing bioenergy projections (primarily stemming from restricted access to updated national livestock statistics and inconsistent monitoring of husbandry practices) has left the economic feasibility of Iran's biogas infrastructure poorly defined. Specifically, the lack of provincial multi-criteria analysis integrating standardized livestock Unit (LSU) density with geographical and climatic variables remains a critical barrier to sector growth. This study bridges this gap through a high-precision assessment of manure-derived biogas potential based on the 2023 livestock census. The technical novelty of this research lies in the application of Livestock Standard Unit equivalents (LSU_e), which enables a normalized, species-specific comparison of production capacities to identify optimal implementation sites with high accuracy. Furthermore, this study proposes a novel economic framework that shifts the strategic focus from biogas-to-power generation toward biogas-to-RNG injection. This approach is specifically tailored to address the surging fuel demands of thermal power plants during peak warm months. Additionally, it provides a strategic resolution to the capital barriers hindering Iran's bioenergy transition by improving key economic indicators to attract investor participation.

MATERIAL AND METHODS

Table 1 presents the animal population in various provinces in 2023 based on census data sources directly from the Ministry of Agriculture-Jihad of Iran. The amount and quality of manure produced by this animal population changes significantly a lot depending on the animal's feed and housing conditions, meaning that biogas and biomethane yield from a tonne of manure can be variable.

This study adopted a reliable, proven methodology that uses standard values for daily manure

Table 1. Animal population 2023 in provinces (Base on animal census data of Ministry of Agriculture Jihad).

Province	Poultry			Heavy Livestock				Small Livestock	
	Laying Hen (Head)	Pullet (Head)	Broiler (Head)	Industrial cattle (Head)	Mixed cattle (Head)	Native cattle (Head)	Buffalo (Head)	Sheep (Head)	Goat (Head)
East Azerbaijan	10,925,244	3,059,348	14,207,660	41,178	267,907	90,574	37,667	3,385,272	506,011
West Azerbaijan	1,174,220	143,000	16,831,340	16,911	236,684	82,350	57,339	3,989,820	369,953
Ardebil	756,380	45,000	8,408,505	23,553	123,648	73,061	42,249	1,928,385	298,162
Isfahan	14,015,249	6,393,581	33,846,796	344,572	333,758	9,082	127	1,567,851	472,167
Alborz	7,764,189	2,818,881	2,704,094	105,649	69,602	223	65	361,808	40,560
Ilam	230,000	-	7,735,500	3,463	20,384	13,223	639	1,394,077	482,348
Busher	40,000	-	6,738,040	831	23,489	8,560	-	437,069	569,208
Tehran	12,034,563	3,945,808	6,157,573	302,753	199,350	4,073	66	988,982	117,609
Chaharmahal and Bakhtiari	409,000	120,000	5,362,300	56,203	111,731	12,820	-	1,319,835	372,549
South Khorasan	2,771,439	1,083,929	10,948,882	13,842	54,587	5,012	-	937,797	895,580
Razavi Khorasan	12,598,536	4,955,485	32,174,372	118,110	312,797	12,375	-	6,721,997	822,008
North Khorasan	130,000	-	3,179,340	7,426	55,458	3,498	-	1,908,516	296,066
Khuzestan	1,096,644	-	20,951,241	10,261	173,233	73,142	100,175	2,572,851	1,067,619
Zanjan	1,119,000	268,000	7,432,510	13,622	44,590	44,717	-	962,444	175,517
Semnan	2,997,700	1,690,000	10,047,700	33,294	52,658	1,394	127	1,476,227	336,474
Sistan and Baluchistan	758,720	60,000	7,215,500	2,432	17,361	47,482	-	1,111,623	1,717,289
Fars	5,669,526	1,295,600	29,241,216	116,800	225,994	42,433	255	3,643,987	2,410,106
Qazvin	9,493,500	5,708,519	9,969,950	133,334	165,195	53,166	127	915,661	112,605
Qom	10,246,480	4,642,120	4,751,800	24,214	47,053	13,065	-	296,758	59,863
Kurdistan	561,000	-	15,209,400	8,000	46,876	91,187	-	1,331,462	294,158
Kerman	2,142,500	242,000	11,209,400	26,905	73,836	9,178	-	1,374,868	1,231,143
Kerman South	100,000	-	288,602	269	26,910	27,462	-	740,256	786,446
Kermanshah	817,000	120,000	9,854,705	23,419	118,843	41,377	127	1,651,415	278,416
Kohgiluyeh and Boyer-Ahmad	570,000	-	2,389,500	4,767	31,802	13,802	-	633,513	868,063
Golestan	5,585,000	2,699,000	36,499,609	22,241	261,243	14,726	2,065	1,576,731	179,101
Gilan	36,000	-	27,245,740	6,408	92,015	125,627	8,272	794,048	93,272
Lorestan	935,000	45,000	15,191,100	10,274	170,360	26,876	255	2,046,238	761,959
Mazandaran	806,400	20,380	40,055,420	15,860	360,064	134,947	2,927	1,513,661	102,921
Markazi	4,943,760	1,545,733	11,859,795	49,637	204,541	8,565	-	1,520,472	211,532
Hormozgan	10,000	-	7,657,620	386	5,208	9,345	-	190,520	989,628
Hamedan	1,887,300	658,000	11,203,910	26,501	289,763	25,771	-	1,419,923	103,048
Yazd	3,615,600	927,000	10,708,350	57,265	82,953	8,627	-	445,898	379,617
Sum	116,239,950	42,486,384	437,277,470	1,620,380	4,299,893	1,127,740	252,482	51,159,965	17,400,998
TOTAL SUM	596,003,804			7,300,495				68,560,963	

Table 2. Coefficients used for the calculation of manure production and biogas production potential. (Ramos-Suárez et al., 2019) (Government of the Canary, 2016)

Animal	Type	w (kg)	LSU$_e$	R$_h$ (kg/head day)	TS (%)	VS (%TS)	Y (m^3 /kgVS)	CH_4 (%)
Cows	Breeding female	550.00	1.00	30.44	20	80	0.333	60.9
	Breeding male	456.50	0.83	15.84	20	80	0.333	60.9
Goats	Breeding female	82.50	0.15	2.30	30	80	0.449	60
	Breeding male	82.50	0.15	2.30	30	80	0.449	60
Sheep	Breeding female	82.50	0.15	2.30	30	80	0.452	55
	Breeding male	82.50	0.15	2.30	30	80	0.452	55
Poultry	Laying hens	5.50	0.01	0.11	40	75	0.447	65.1
	Broilers	2.75	0.005	0.11	40	75	0.447	65.1

W: Average weight; LSU$_e$: Livestock Standard Unit equivalent; Rh: Manure production; TS: total solids content in manure; VS: volatile solids content, with respect to total solids; Y: biogas yield; CH_4: biogas methane content.

production by animal type and species, and applies specific manure and biogas production coefficients sourced from trusted international research projects. (small biogas, 2014) (Alfonso et al., 2009). This approach ensures that final calculations are scientifically reflective of real conditions. To calculate and compare the animal population size of provinces with different animal species and types, livestock standard unit equivalent (LSU$_e$) for each type and species were obtained using the conversions shown in table 2 (Ramos-Suárez et al., 2019) (Government of the Canary, 2016). Manure generation and biogas production potential were calculated using equations (1) and (2). The energy and electricity generation potentials were calculated from the estimated biogas yield and the conversion efficiency of the generators, using Equations (3) and (4)

$$R_h = \sum_h A_{ij} \times Q_{ij} \tag{1}$$

where R_h is the daily amount of manure produced in province h (kg/day), A_{ij} is the number of animals of species i and type of animal j; and Q_{ij} is the daily amount of manure produced by the type of animal j of species i.

$$B_h = \sum_h A_{ij} \times Q_{ij} \times TS_{ij} \times VS_{ij} \times Y_{ij} \tag{2}$$

where B_h is the daily biogas volume produced in province h (m^3/day), TS_{ij} is the total solids content in manure Q_{ij} (%/100), VS_{ij} is the volatile solids content, with respect to total solids, in manure Q_{ij} (%/100), and Y_{ij} is the biogas yield for manure Q_{ij} (m^3/kgVS).

$$Pb_h = \frac{LHW_{CH4}}{24} \sum_h B_{ij} \times CH4_{ij} \tag{3}$$

where Pb_h is the gross power from biogas in province h (kW), B_{ij} is the daily biogas volume produced in province h from waste of species i and animal type j (m^3/day), $CH4_{ij}$ is the methane content of biogas produced in province h from waste of species i and animal type j (%), and LHW_{CH4} is the lower heating value (9.94 kWh/m^3).

$$P\partial_h = Pb_h \frac{\eta_e}{100} \tag{4}$$

where $P\partial_h$ is the electrical power from biogas in province h (kW_e); and η_e is the average electrical efficiency of biogas generators (35%).

Determining collectability coefficient

According to the 2019 report of the World Biogas Association (WBA, 2019), manure collectability is defined by average housing coefficients. In this study, while the 75% coefficient for poultry was adopted directly from the report. those for cattle and small livestock were adjusted to account for Iran's unique husbandry and climatic conditions. The necessity for this localization arises from the fact that over 98% of Iran's territory could be classified as hyper-arid, arid, or semi-arid arid or semi-arid regions (Mesgaran et al., 2017), rendering standard global grazing assumptions unsuitable for the local context. Consequently, these coefficients were estimated based on domestic conditions and national statistics, as follows:

• Heavy Livestock (cattle): According to Table 2, Iran has approximately 7.3 million head of heavy livestock, of which 5.9 million are industrial breeds. Native calves and buffaloes were excluded from the coefficient calculation due to limited manure collection. Accordingly, the share of industrial heavy livestock in the total heavy livestock population is estimated at 81%.

• Small Livestock: a 42% coefficient was calculated using the 2023 Agricultural Yearbook (SCI, 2025). Data indicate that 87% of Iranian farmers are rural, 34% of whom are nomadic; this nomadic segment was excluded due to the lack of manure collection potential in mobile systems. For the remaining non-migratory rural livestock population, a six-month seasonal grazing adjustment was applied, identifying 28.5 million head out of the 68.6 million national total from which manure collection is feasible.

The resulting manure collectability coefficients are summarized in Table 3.

Table 3. Manure collectability coefficient (C_h).

Poultry (%)	Cattle (%)	Sheep and Goat (%)
75	81	42

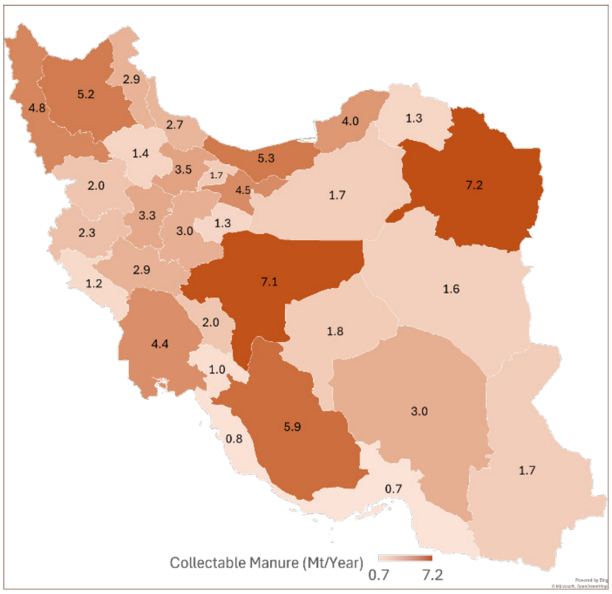

Fig. 2. Provincial livestock collectible manure in (Mt/Year).

RESULT AND DISCUSSION

As presented in Table 1, the poultry sector comprises a population of approximately 596 million birds, while the populations of small and heavy livestock total 68.5 million head (sheep and goats) and 7.3 million head (predominantly cattle), respectively. From this animal population, this study determines that the total annual fresh manure production reaches 143.1 Mt, with the total annual collectible manure estimated at 92.1 Mt. The primary contributors to this collectible volume are cattle (54.2%), followed by small livestock (26.3%) and poultry (19.5%). As illustrated in Fig. 2, ten provinces generate in excess of 4 Mt of collectible manure annually, providing a robust feedstock base for the development of large-scale biogas facilities.

The aggregate biogas production potential derived from collectible manure is estimated at 7,668 Mcm, with the provincial-level distribution delineated in Fig. 3. Notably, the results indicate that the province with the highest manure production does not consistently exhibit the highest biogas yield. This discrepancy underscores the critical influence of manure source composition and the distribution of species types expressed in LSUe in provinces. Consequently, the specific mix of animals within a local population is a primary factor in determining a province's energy potential (as demonstrated by the comparison of Mazandaran and Fars Provinces).

Evaluation of Biomethane production and electricity generation potential.

Incorporating provincial variations in manure source composition (comprising cattle, small livestock and poultry) the aggregate biomethane production potential is estimated at 4,662 Mcm per annum, representing the 60.6% methane fraction of the total biogas volume. On a national scale, this volume can constitute approximately 2.0% of Iran's total natural gas consumption, which reached 237,907 Mcm in 2024 (VCM, 2024). The provincial-level substitution potential (the percentage of natural gas consumption that could be displaced by biomethane production) is illustrated in Fig. 4. Furthermore, the total theoretical electricity generation potential

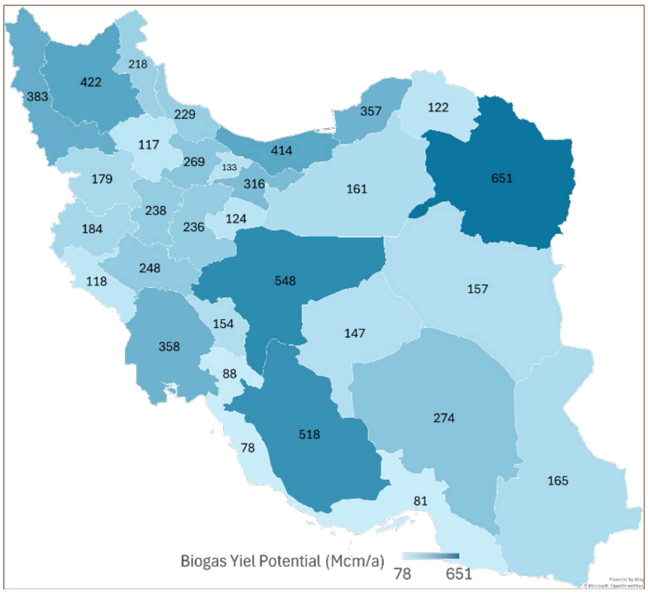

Fig. 3. Provincial biogas production potential in provinces (Mcm/Year).

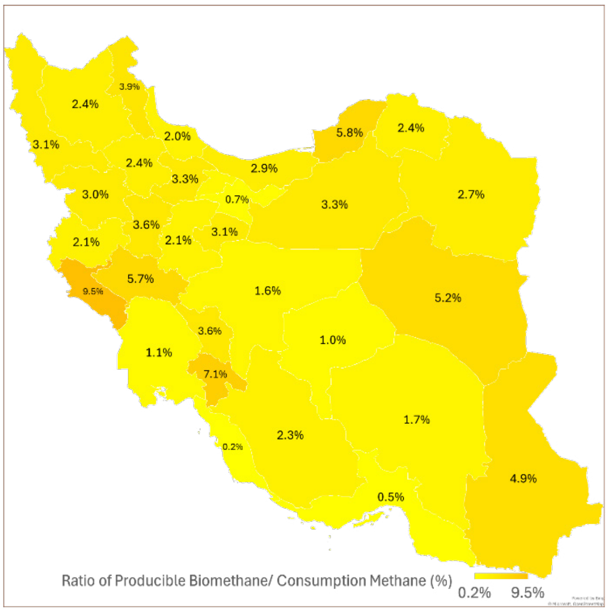

Fig. 4. Provincial natural gas substitution potential (%) through provincial biomethane production.

is quantified at 16,217 GWh, representing 5.1% of the national electricity demand in 2023 (316,584 GWh) (TAVANIR, 2023). Fig. 5 delineates the extent to which current provincial electricity demand could be offset through biomethane-to- electricity power conversion.

A solution to compensate for natural gas imbalance

Figure 6 presents the sectoral breakdown of Iran's average daily natural gas consumption, disaggregated by month for the Solar Hijri year 1402 (April 2023 – March 2024). The data highlights seasonal fluctuations in consumption patterns across various economic sectors. Notably, the thermal power generation sector experiences a significant escalation in gas consumption during the peak period (June–September). As depicted in Figure 7, consumption

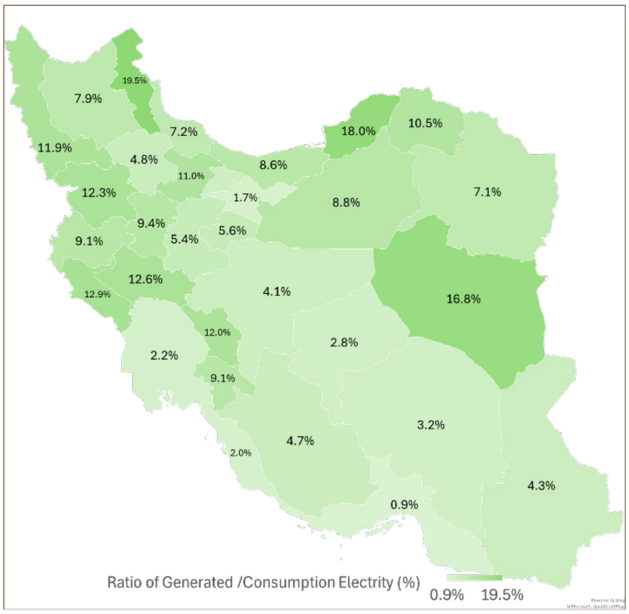

Fig.5. Provincial electricity demand offset potential (%) through provincial biomethane-to- electricity power conversion.

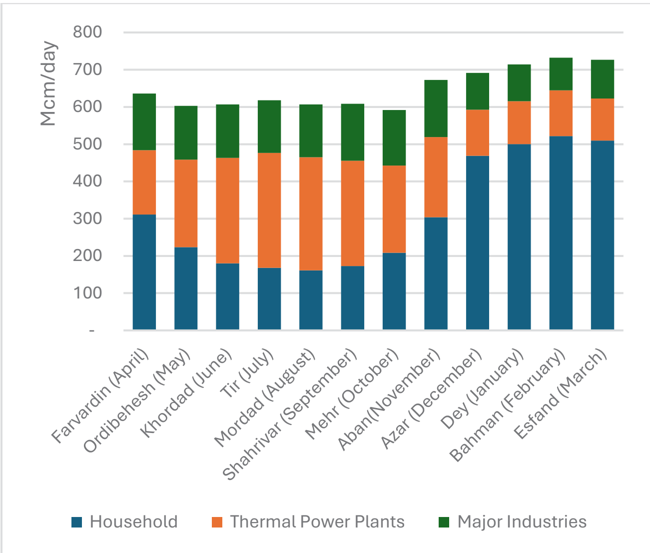

Fig. 6. Diagram of sectoral and monthly distribution of Iran's average daily natural gas consumption

reached an apex of 309 Mcm/day in July (SCI, 2025; VCM, 2024).

Detailed analysis of this four-month interval indicates a mean daily increment of 85 Mcm, corresponding to a total monthly consumption growth of 2,650 Mcm compared to the preceding months. Given that the estimated annual biomethane production potential from livestock, strategic storage and peak deployment could offset the incremental consumption for approximately two months of the four-month peak period.

A New Economic Framework for Overcoming Capital Barriers in Iran's Bioenergy Market

This study proposes a novel economic framework that reconfigures the strategic focus from conventional biogas-to-power generation to biogas-to-RNG injection plants. Approximately 51.52% of the capital expenditure (CAPEX) of a standard biogas power plant is dedicated

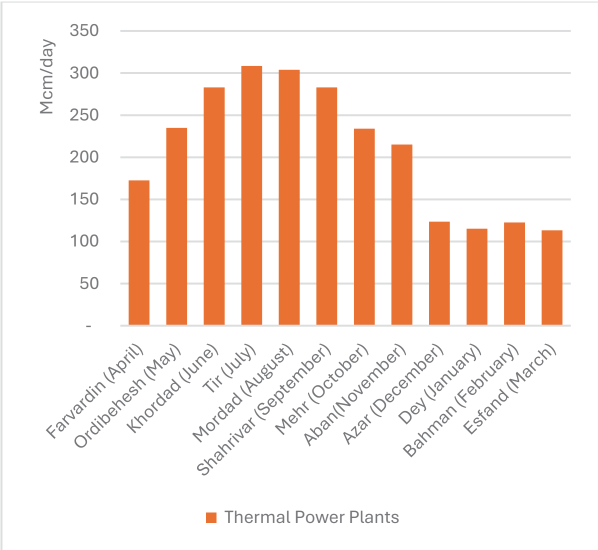

Fig. 7. Diagram of monthly distribution of average daily natural gas consumption in thermal power plant

to power generation components and grid connection equipment (Akbulut et al., 2021). By decoupling these electrical units, the required initial investment is significantly reduced, thereby lowering the market entry barrier for private developers. Under this model, biogas plants inject produced biomethane directly into the national distribution gas pipelines. Concurrently, through the enactment of new regulations, the government will mandate the its Ministry of Energy (MOE) to store the produced biomethane in its existing storage tanks or to develop dedicated storage infrastructure. Furthermore, these regulations will require the MOE to enhance the efficiency of its thermal power units and optimize the electricity-to-fuel ratio, thereby maximizing the economic value of each cubic meter of gas.

Rather than purchasing electricity from biogas power plants under feed-in tariff arrangements at an export-equivalent rate of USD 0.065/kWh (MOE, 2026), the MOE procures biomethane directly at an export-equivalent rate of USD 0.20/m^3. Consequently, if the MOE can increase the efficiency of its thermal power plants beyond 30.8%, it will realize a net economic benefit from this strategic energy substitution.

The government by investing, not only strengthens national energy security but also improves overall electricity generation. Furthermore, stored biomethane serves as an important reserve that can be used during periods of peak demand, when thermal power plants often face fuel shortages or seasonal supply deficits. From the private sector's perspective, the substantial reduction in capital expenditure, together with the elimination of operational costs associated with maintaining complex electrical systems, creates a much more attractive investment environment for private stakeholders.

To validate this framework, a comparative economic analysis was conducted between a biogas-to-power scenario and the proposed biogas-to-RNG injection model. For this purpose, the design and commissioning costs of a biogas power plant were estimated for a poultry farm with 200,000 broiler heads located in Qazvin Province, Iran. The operational parameters of the poultry farm and the specifications of the modeled power plant are detailed in Table 4. Based on these specifications, a 461kW biogas power plant was proposed with an estimated total investment cost of USD 1.267 million, equating to approximately USD 2,742/kW. This estimate is consistent with the findings of the 2025 IRENA report, which indicates ranges from USD 1,500/kW in India to USD 3,900/kW in North America, with a global weighted average of USD 3,242/kW in 2024 (IRENA, 2025b).

Table 4. operational parameters of the poultry farm and the specifications of the modeled power plant.

	Unit	Status / Amount
Biogas power plant system	-	Anerobic digesting with two digesters in series
Temperature of digesters	^{o}c	Mesophilic conditions (40 ^{o}c)
Poultry head population	head	250,000 broiler hens
Daily poultry manure production	tonnes	32.5
Organic load rate (OLR)	kg ODM/m^3	4.38
Hydraulic retention time (HRT)	day	39
Ratio of manure and water mixing	-	1:3
Biogas desulphurization system	-	Condensation with Physical adsorption (Hematite)
Manure inlet per year	Mt/a	11,863
Biogas production per year	m^3/a	1,590,761
Methane production per year	m^3/a	1,035,586
power plant capacity	kW	461
Total efficiency of CHP	%	80.26
Electrical efficiency	%	39.27
Producible electrical energy per year	kWh/a	4,042,344
Internal electrical energy consumption per year	kWh/a	211,819
Internal electrical energy losses per year	kWh/a	69,933
Useable electrical energy per year	kWh/h	3,760,593

Table 5. Comparative economic analysis of biogas-to-power with biogas-to-RNG injection.

Biogas power plant - sale of generated electricity			**Biogas plant - sale of produced biomethane**		
Total capital expenditure (CAPEX)	**USD**	**1,267,190**	**Total capital expenditure (CAPEX)**	**USD**	**614,940**
power plant nominal power	kW	461	Biogas installed Capacity	Nm^3/h	181.6
Capex per kW	USD/kW	2,749	capex per m^3	USD/kW	3,386
Cash Flow			**Cash Flow**		
Total annual expenses		**144,338**	**Total annual expenses**		**80,758**
Annual operational expenditure (OPEX)	USD (5% Capex)	50,738	Annual operational expenditure (OPEX)	USD (5% Capex)	24,598
Annual personnel expenditure	USD (10 Person)	93,600	Annual personnel expenditure	USD (6 Person)	56,160
Annual Income		**304,160**	**Annual Income**		**266,838**
Electricity sales rate	USD/kWh	0.065	Biomethane sales rate	USD/m^3	0.20
Annual net electricity generation	kWh/a	3,760,593	Annual biomethane yield	m^3/a	1,035,586
Solid digestate rate	USD/tonne	15	Solid digestate rate	USD/tonne	15
Annual solid digested production	tonne	3,981	Annual solid digested production	tonne	3,981
Economic indicators			**Economic indicators**		
Inflation rate	%	3.5%	Inflation rate	%	3.5%
Discount rate	%	4.5%	Discount rate	%	4.5%
Project lifespan	Year	20	Project lifespan	Year	20
Net LCOE (electricity)	USD/kWh	0.0539	LCOB (biomethane)	USD/m^3	0.10
Net present value (NPV)	Positive	702,633	Net present value (NPV)	Positive	2,240,557
Internal rate of return (IRR)	%	9.2%	Internal rate of return (IRR)	%	29 %
Payback period	Year	10	Payback period	Year	4

As represented in Table 5, although the levelized cost of electricity (LCOE) for a poultry-based biogas facility is estimated at 0.053 USD/kWh, the resulting marginal profitability is insufficient to incentivize private investment given the high-risk profile and substantial upfront costs of power generation. The economic evaluation demonstrates that transitioning to a biogas-to-RNG framework achieves a 51.52% reduction in capital expenditure. Most significantly, this model enhances profitability by more than tripling the IRR from 9.2% to 29% and reducing the payback period from ten to four years, ultimately restoring the commercial viability of biogas projects.

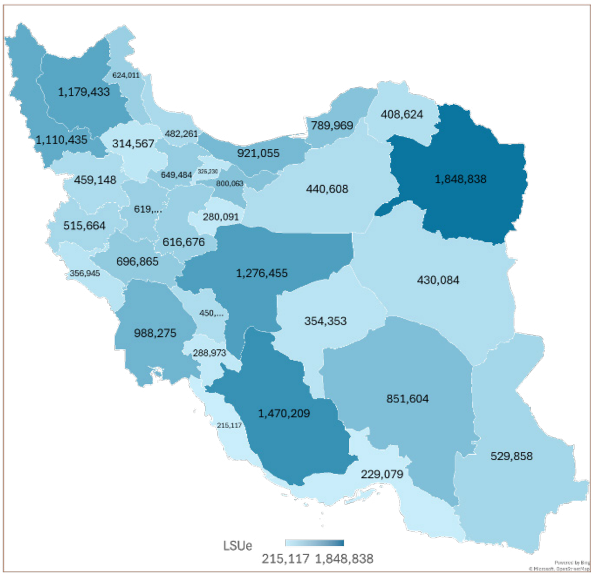

Fig. 8. Livestock Standard Unit Equivalent (LSU_e) in Provinces.

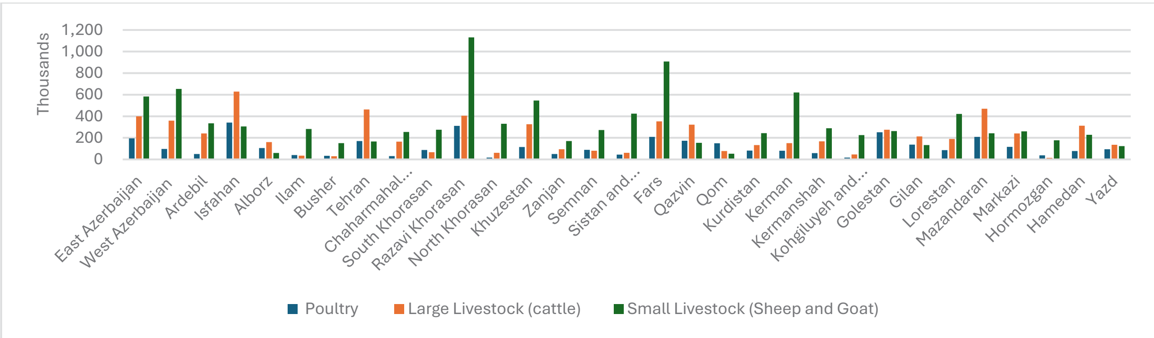

Fig. 9. Distribution of species types expressed in LSU_e in provinces in 2023

Livestock Standard Unit Equivalent in Provinces

To effectively compare the scale of the livestock industry across provinces with diverse animal compositions, standardized measures of the Livestock Standard Unit (LSU) were utilized. This metric converts various species into a common unit based on their feed or energy requirements (FAO, 2011), providing a more accurate basis for government policy and subsidy decisions than simple animal headcounts. In total, Iran's livestock population amounts to 20.5 million LSU_e, comprising 10.3 million small livestock, 6.7 million large livestock, and 3.5 million poultry. Geographically, the distribution of these standardized units is highly uneven, with Razavi Khorasan, Fars, and Isfahan collectively hosting over 22% of the national LSU_e (Fig. 8).

Fig. 9. illustrates reveals significant imbalances in resource consumption. Although poultry constitute the vast majority of animals by headcount, they account for only 17.4% of total energy demand. In contrast, small livestock (sheep and goats) consume half (50.1%) of the nation's feed energy, followed by cattle (32.5%). This high energy use is surprising because small livestock actually contribute the least to the average Iranian household diet (SCI, 2025). As they are raised only for meat (unlike poultry and cattle that provide both meat and eggs or milk) small livestock are highly "energy expensive" relative to their output and generate elevated greenhouse gas emissions. Therefore, shifting toward larger, more efficient livestock would provide better economic and environmental benefits.

Table 6. Biogas and biomethane yield per unit of manure tonne per LSU_e.

Metric	Biogas yield (m^3)	Biomethane yield (m^3)	LSU_e composition
Per tonne of fresh manure	83.5	50.6	50.1% Sheep & Goats, 32.5% Cattle, 17.4% Poultry
Per LSU_e unit	374.5	227.2	

Standardizing Bioenergy Metrics through Livestock Standard Equivalents

Table 6 details the estimated production capacities for biogas and biomethane per tonne of fresh manure. To ensure accurate comparisons and account for differences in population sizes, these energy yields have been carefully adjusted based on the distribution of livestock categories, using the Livestock Standard Unit (LSUe). Furthermore, to provide practical data for long-term energy planning, the table calculates the additional bioenergy potential generated by each new LSUe. By including these incremental values, the forecast directly accounts for the expected population growth within the livestock and poultry sectors. This creates a clear, forward-looking model of how agricultural waste can contribute to future energy needs.

Optimizing Site Selection

The previous analysis established that one tonne of composite fresh animal manure yields approximately 50.6 m^3 of biomethane. To operate a biogas plant with flow rate of 2,875 Nm^3/h (~10 MW biogas power plant), a daily supply of 68,985 m^3 of biomethane is required. This demand can be met by processing approximately 1,363 tonnes of animal fresh manure per day. Given that the average daily manure production in each province is 8,137 tonnes, it is theoretically feasible to support an average of six decentralized 2,875 Nm^3/h biogas plants per province. Table 7 shows the potential number of biogas plants that could be established across the provinces.

The economic viability of biogas plant projects is significantly influenced by the distance required for feedstock collection (Topić et al., 2020). Consequently, the density of LSU_e per unit area is a critical factor in site selection. A collection area with a radius of 25 km (UABIO, 2013) (Reparaz et al., 2021)(1,962 km^2) is commonly considered an economically important area for such facilities. Based on a comparison of provincial areas with the number of constructible 2,875 Nm^3/h biogas plants against this economic area as detailed in Table 7, the provinces of Tehran, Alborz, Mazandaran, Qazvin, and Golestan meet the initial suitability conditions. However, Tehran and Alborz provinces are assigned a lower priority for site selection due to factors such as high population density, challenging topography, and limited diversity in suitable water resources (prioritizing wastewater, surface water, and groundwater), making Mazandaran, Qazvin, and Golestan provinces more favorable.

Biomethane-producing bacteria, essential for anaerobic digestion, exhibit peak activity within specific temperature ranges. These are generally categorized as mesophilic, typically between 30–40 °C, and thermophilic, ranging from 50–60 °C (Asadinejad et al., 2016). Considering the temperatures of the Iranian provinces (Mahmoudi et al., 2019), Qazvin, with its low average annual temperature, was assigned a lower priority for biogas plant construction. This is likely due to less favorable thermal conditions for microbial processes and the consequent need for additional heating energy. Consequently, the Mazandaran and Golestan provinces have emerged as the most suitable initial locations for establishing biogas plants, with successful projects in these regions potentially catalyzing the broader expansion of biogas infrastructure across Iran.

Table 7. Comparative key characteristics of provinces for siting biogas plants.

Province	Province's population 2023 (Head) (IEA, 2025; SCI, 2025; TAVANIR, 2023)	Province's average temperature (ºC) (IRIMO, 2023; SCI, 2025)	Province's Area (Km^2) (SCI, 2025)	Number of constructible 2,875 Nm^3/h biogas plant	Area to No. of biogas plants ratio
East Azerbaijan	4,075,000	15.0	45,468.86	10	4,565
West Azerbaijan	3,502,000	13.5	37,542.95	9	4,157
Ardebil	1,298,000	11.8	17,875.54	5	3,560
Isfahan	5,402,000	18.8	107,116.09	15	7,134
Alborz	2,992,000	17.1	5,182.03	3	1,708
Ilam	596,000	17.8	20,164.11	2	10,066
Busher	1,265,000	26.5	22,896.07	1	22,742
Tehran	14,287,000	19.7	13,538.43	9	1,521
Chaharmahal and Bakhtiari	993,000	12.4	16,251.89	3	5,443
South Khorasan	836,000	18.1	152,018.28	3	50,266
Razavi Khorasan	7,036,000	17.7	119,063.87	13	9,142
North Khorasan	876,000	15.0	28,371.68	2	14,217
Khuzestan	5,075,000	27.7	64,526.16	8	8,007
Zanjan	1,114,000	13.5	21,733.12	2	10,887
Semnan	777,000	20.1	97,750.92	3	32,497
Sistan and Baluchistan	3,214,000	20.5	182,312.13	2	90,893
Fars	5,111,000	19.1	122,199.36	11	10,964
Qazvin	1,340,000	16.2	15,594.92	7	2,224
Qom	1,435,000	20.5	11,454.75	2	5,763
Kurdistan	1,682,000	15.6	29,201.32	4	7,284
Kerman	3,385,000	17.8	181,152.28	5	36,545
Kermanshah	1,998,000	16.3	25,186.86	4	6,252
Kohgiluyeh and Boyer-Ahmad	755,000	16.1	15,474.65	1	15,504
Golestan	2,002,000	19.1	20,477.23	8	2,546
Gilan	2,567,000	18.2	13,988.14	5	2,808
Lorestan	1,793,000	18.0	28,090.74	5	5,659
Mazandaran	3,401,000	19.8	23,719.23	11	2,167
Markazi	1,469,000	16.1	29,196.19	6	4,855
Hormozgan	1,989,000	28.0	71,228.63	1	70,697
Hamedan	1,769,000	13.6	19,372.20	6	3,228
Yazd	1,293,000	22.1	73,823.83	3	24,624
Sum	85,327,000		1,631,972	169	

CONCLUSION

This study provides a high-precision framework for mobilizing Iran's livestock manure resources to mitigate the country's chronic seasonal energy imbalances. By applying a localized collectability coefficient (81% for heavy livestock and 42% for small livestock) and the novel LSU_e methodology, the research identifies a national potential of 92.1 Mt of collectible manure annually. This volume translates into a biomethane potential of 4,662 Mcm per year, capable of substituting 2.0% of Iran's total natural gas consumption or generating 16,217 GWh of electricity (representing 5.1% of the household demand).

The core innovation of this research is the proposed strategic transition from biogas-to-electricity systems to a biogas-to-RNG injection model. The economic evaluation demonstrates that by decoupling power-generation infrastructure, capital expenditure is reduced by 51.52%. This shift significantly enhances project feasibility, increasing the IRR from 9.2% to 29% and shortening the payback period from 10 years to just 4 years. Critically, the daily biomethane output of 12.7 Mcm can be stored within the national grid to offset nearly two months of the 85 Mcm/day peak demand surge typically experienced by thermal power plants during the summer.

Geospatial analysis identifies Mazandaran and Golestan as the most favorable provinces for initial deployment, due to their high LSUe density, favorable climatic conditions, and logistical feasibility. Policy recommendations emphasize the necessity of transitioning from micro-scale biogas plant to high-capacity biogas infrastructure (e.g., 2,875 Nm^3/h biogas plant) supported by export-parity pricing (USD 0.20/m^3) and long-term feedstock contracts. Environmentally, this framework offers a dual benefit: avoiding 131.9 Mt of CO_{2eq} through methane abatement and an additional 7.3 Mt of CO_2 via fossil fuel substitution. Ultimately, adopting this biomethane-centric model provides the Iranian investors with a low-risk, high-return pathway to enhance energy security while meeting international decarbonization targets. Future research should focus on the life cycle assessment (LCA) of the biomethane-to-grid pathway and the integration of carbon credit markets to further bolster the economic incentives for the Iranian bioenergy sector.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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