ORIGINAL RESEARCH ARTICLE

A Public Health–Oriented Assessment of Renewable Energy Opportunities and Threats at a Municipal Waste Disposal Site: A SWOT Analysis (Karaj Landfill, Iran)

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Abstract

Background Waste disposal sites create serious health problems through air pollution and greenhouse gases, but they also offer good chances for clean energy production that can improve community health. This research looked at the good points, bad points, opportunities and threats of using renewable energy at Karaj's Halghe Darreh landfill site, focusing on landfill gas and solar power projects.

Methods We used a combination of number-based calculations and qualitative SWOT analysis. Landfill gas potential was calculated using the standard LandGEM model, while solar power estimates used common yield equations. Data came from official reports of Karaj Waste Management from January to June 2023, plus relevant policy documents and regulations.

Results The landfill receives about 550 tons of waste daily. Landfill gas could produce around 41,917 MWh of electricity yearly (about 114.84 MWh daily), enough for 35,000 homes while cutting methane emissions equal to 1.2 million tons of CO_2 yearly. Solar power on 50 hectares of closed landfill areas might generate nearly 14,000 MWh per year. Good factors include existing gas systems, legal support through power agreements, location near power grid, and institutional backing. Main problems are high costs (150-200 billion tomans), dust reducing solar panel efficiency by 25-30%, unstable policies, and land use conflicts.

Conclusion The Halghe Darreh landfill can successfully develop renewable energy with important health benefits. Immediate steps should include small-scale landfill gas projects to cut methane and improve air quality, then solar farms on unused landfill areas, using public-private partnerships to handle costs. This approach can turn the landfill into a resource recovery site that improves energy supply, reduces health risks, and offers a model for other Iranian cities.

Keywords Environmental health, Landfill pollutant, Public health, Sustainable development, Waste management

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1 Introduction

Urban waste sites are increasingly seen as places for energy production rather than just dumping waste.[1] This change fits with circular economy ideas where waste becomes a resource for energy while cutting greenhouse gases.[2,3]

Cities in Iran are growing fast and producing more waste, making waste management harder.[1,4] Renewable energy comes from natural sources like sun, wind, and waste that renew themselves. These sources are good alternatives to fossil fuels and help solve environmental and political problems.[4,5]

Karaj is a large city near Tehran with high population density, so it makes a lot of waste.[6] Most of this waste goes to the Halghe Darreh Waste Center. Besides using much land, this site releases large amounts of methane gas which harms the environment and people's health.[7,8] When we capture this gas, it can become useful energy instead of pollution. Environmental worries, rising energy costs, and energy security have made renewable energy more popular worldwide.[9,10] Studies in Tehran using GIS and AHP methods showed good potential for renewable energy, with about 32% of the area suitable for wind power and 8% good for solar farms.[11-13]

The Halghe Darreh center has lots of organic waste, available land, and good location for renewable energy.[14] Main options are getting energy from landfill gas and putting solar panels on closed landfill areas. But there are challenges too - environmental, economic, technical, and regulatory ones.[15,16]

More waste plus environmental limits on traditional waste handling means we need better systems that recover resources.[2,17] Adding renewable energy to waste sites can cut greenhouse gases, make electricity on site, lower costs, and create income from selling extra power.[3,17]

Good decisions need to understand both opportunities and problems. Things like policies, weather, existing systems, and public acceptance affect whether projects work well.[18,19] With energy crises, climate change, and smart city ideas, checking renewable energy at waste sites has become important for city planning.[10,20]

Many studies exist on getting energy from waste in Iran, but some gaps remain. Most research looked at solar or wind power alone, not combining them at waste sites.[21,22] Landfills have lots of organic material and unused land but aren't used enough for combined renewable systems.[23,24]

Also, few studies looked at medium-large cities outside Tehran. Karaj and Alborz Province haven't been studied much despite their size and waste amounts.[6,21] Most research focused on technical and money issues, ignoring non-technical problems like policies, public acceptance, and legal barriers that often stop projects from happening.[18,19,25]

This study used SWOT analysis to check renewable energy at Karaj's waste center. As far as we know, no one has used SWOT for this site before to find energy opportunities and threats. This approach makes our study both new and useful.[25,26]

2 Methods

Study Area and Data Collection

The research focused on Halghe Darreh Waste Center in northwest Karaj, Iran. This facility handles waste from Karaj city and western Tehran districts. Total daily waste intake averages around 1,500 metric tons. However, a key clarification is needed here: not all this waste ends up in landfill cells. Data from January to June 2023 shows only about 550 tons per day (roughly 37% of total) actually gets landfilled. The remainder follows different paths - approximately 700 tons goes to composting units, 200 tons to recycling lines, and 50 tons to pyrolysis treatment. Figure 1 visually demonstrates this waste flow pattern, making the distinction between total incoming waste and actual landfill disposal much clearer. We obtained these quantitative figures directly from Karaj Waste Management's official monthly reports for the first half of 2023. These documents contain detailed waste composition data and infrastructure specifications that aren't publicly available elsewhere.[14]

For policy and regulatory context, we analyzed municipal bylaws, Islamic City Council resolutions, and national energy documents from Iran's Renewable Energy Organization (SATBA).[27] This dual approach ensured we captured both operational realities and policy frameworks affecting renewable energy implementation.

Energy Potential Calculation Methodology

We used the LandGEM model (recommended by US EPA) for landfill gas potential estimation.[28,29] The technical potential for landfill gas-based energy recovery was estimated using the Landfill Gas Emission Model (LandGEM) as endorsed by the United States Environmental Protection Agency, based on the following equation:[30]

$$Q_g = \frac{1}{C_{CH_4}} \sum_{i=1}^{n} \sum_{j=0.1} kL_0 \left(\frac{M_i}{10}\right) e^{-kt_{ij}}$$

- Qg = landfill gas generation rate (m^3 /year)
- CCH4 = methane volume concentration (default value of 50%)
- k= first-order decay rate constant ($year^{-1}$)
- L0= methane generation potential (m^3 / ton of waste)
- Mi= mass of waste disposed in the ith year (tons)
- tij = age of the jth section of waste mass disposed in the ith year (years)
- i = year increment (1-year)

- jj = year increment (0.1-year)
- n = calculation year minus initial year of waste acceptance

For solar energy calculations, standard yield equations were applied with regional meteorological data. Rather than repeating the detailed formulas already presented in the abstract, we'll focus here on the practical application and parameter choices. Regional solar irradiance was set at 5.75 kWh per m² per day based on GIS-derived estimates for this area.[15,29] We selected 18% as panel efficiency (typical for commercial polycrystalline modules available in Iran) and applied a 30% loss factor to account for dust accumulation - a significant issue we observed during site visits.[31,32] This practical adjustment reflects real-world conditions better than theoretical maximum values.

SWOT Analysis Framework

The SWOT analysis involved exactly eight specialists, carefully selected using specific criteria:

- **Selection requirements**

Each expert needed minimum 5 years of hands-on experience in waste management or renewable energy, documented involvement in at least one relevant project within the past three years, plus appropriate academic qualifications or professional certifications.

- **Expert breakdown**

We included three Karaj Municipality waste professionals (each with over 10 years field experience), two renewable energy engineers from Tehran University and Sharif University, two environmental health specialists (one from a medical university and one from an environmental research institute), and one policy analyst from SATBA.

The process wasn't purely formal - we conducted three-day workshops where experts could debate and challenge each other's perspectives. Each SWOT factor received scores on both importance and feasibility using a 5-point scale. We then developed strategic options by matching internal capabilities (strengths/weaknesses) with external conditions (opportunities/threats) through SO, ST, WO, and WT matrices.[25,26]

This practical approach generated more realistic recommendations than purely theoretical analysis would have produced.

3 Results

Quantitative Energy Potential Assessment

The Halghe Darreh landfill receives about 550 metric tons of waste daily that goes directly into landfill cells.[14] Using the LandGEM model, we calculated that this waste could generate roughly 114.84 MWh of electricity every day - that's about 41,917 MWh per year. To put this in perspective, this amount of power could supply electricity to around 35,000 homes in Karaj each year. An important side benefit is that capturing this landfill gas would prevent methane emissions equivalent to nearly 1.2 million tons of CO_2 over a century.[19,29]

Table 1 shows how waste is handled at Halghe Darreh during the first half of 2023. Figure 1 gives a clear visual breakdown of waste composition with percentages for each category and a detailed legend explaining the different waste streams.

Table 1 Waste status at the Halghe Darreh Waste Disposal and Processing Center during the first half of 2023 (tons per day)

Waste category	Amount
Total incoming waste	1,500
Rejected, landfilled waste	550
Pyrolyzed waste	50
Recycled waste	200
Compost production	700

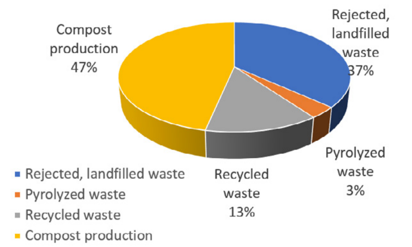

Figure 1 Waste composition distribution at Halghe Darreh Waste Disposal and Processing Center (first half of 2023).

The facility covers roughly 120 hectares of land. About 50 hectares of this area consists of closed landfill sections that could potentially hold solar panels. Based on local weather data showing average solar radiation of 5.75 kWh per square meter daily, and considering that dust reduces panel efficiency by about 30%, each square meter of solar panel would produce around 1.035 kWh daily.[31,32]

A full-scale solar installation across 50 hectares could generate approximately 13,250 MWh of electricity annually - enough to power the entire waste facility with extra electricity to feed into the national grid.

Qualitative SWOT Analysis Results

Strengths

1. Steady supply of 550 tons daily of organic waste suitable for biogas production.[14]
2. Existing gas collection pipes and equipment that can be upgraded for power generation.[15,29]
3. Plenty of available land plus strong sunlight (5.5 to 6 kWh per m² daily).[13,15]
4. Advanced waste processing already operating - composting and pyrolysis units are functional.[2]

5. Good location near power lines and western Tehran's populated areas.[27]

Weaknesses

1. Energy policies keep changing, making long-term planning difficult.[33]
2. Municipal staff need more training on renewable energy systems.[33]
3. Very high startup costs - between 150 to 200 billion Iranian tomans.[34]
4. Waste isn't sorted well at source, which could lower gas quality.[19]
5. Heavy dust cuts solar panel output by 25-30% during summer months.[32,34]

Opportunities

1. Government guarantees to buy renewable power through official agreements.[27]
2. New national focus on sustainable cities and circular economy concepts.
3. Close to universities that can provide technical help and research support.[18]
4. Can start small with pilot projects before committing to big investments.[10]
5. International banks might fund infrastructure projects like this one.

Threats

1. Renewable energy subsidies keep changing with each new government.[34]
2. The city keeps expanding and wants this land for housing or parks.
3. Iran's economy makes it hard to get stable financing for long projects.
4. Permits take much longer than expected - sometimes 6-8 months for simple approvals.
5. Equipment breaks down faster here than manufacturers claim due to dust and heat .Looking at all factors together, the positive aspects (strengths and opportunities) appear stronger than the challenges (weaknesses and threats). The financial and technical problems are real, but they can be overcome with proper planning and the right partners. Similar facilities in other countries have succeeded despite facing comparable difficulties.

4 Discussion

Halghe Darreh site may produce excess of 55,000 MWh/year using landfill gas and solar integration. This capability is consistent with global trends, as integrated waste-to-energy systems have become widely adopted in sustainable practices. Europe now hosts in excess of 500 landfill gas facilities, while the United States has over 600 operational projects generating over 10 terawatt-hours annually.[28,35]

Nonetheless, these global precedents are subject to dissimilar regulatory and economic contexts compared to current conditions in Iran. The SWOT analysis indicates multiple strengths within the facility that could facilitate the adoption of renewable energy. The current gas extraction framework presents a strong starting point, and Iran's Renewable Energy Organization SATBA provides legally valid power purchase agreements that mitigate market volatility. This context is more conducive than many previous Iranian studies have recognized. Prior investigations frequently emphasized technical feasibility while neglecting practical implementation considerations such as policy endorsement and institutional capabilities.[19]

The primary obstacle remains financial. The projected 150-200 billion tomans necessary for complete implementation constitute a significant expenditure for Karaj Municipality. Nonetheless, global trends indicate such systems may achieve economic sustainability. U.S. studies indicate 5–7-year payback periods when factoring in carbon credits, tax incentives, and lower long-term closure expenses.[36] Mexican data indicate that hybrid biogas-solar systems can produce 25-26 megawatts of renewable energy, confirming the feasibility of combined systems.[20]In Tehran, experimental results indicate that anti-dust coatings, when paired with automatic cleaning mechanisms, can enable panels to retain 90% efficiency under dusty conditions.[31]

Such alternatives involve further financial outlay but are operationally viable. It is most logical to proceed with a phased implementation. Implementing small-scale landfill gas initiatives during the initial year enables the municipality to assess technologies and develop expertise without making significant investments. Public-private partnerships are effective in analogous Iranian scenarios - Tehran achieved a 22% cost reduction in solar projects through this approach.[27]

This strategy enhances institutional capabilities and mitigates financial exposure. Public health considerations constitute an additional significant factor frequently excluded from prior analyses. The uncontrolled release of landfill gas is a significant concern, as it contains volatile organic compounds that contribute to the formation of ground-level ozone, a known asthma trigger and factor in reduced pulmonary function, particularly impacting children residing near waste facilities.[19]

Methane extraction systems would mitigate these health hazards and also reduce greenhouse gas emissions. Likewise, solar infrastructure on capped landfills addresses the issue of open burning, which emits dioxins and particulate matter, both classified as Group 1 carcinogens by global health authorities.[34]

This study presents notable limitations worth addressing. Firstly, our estimations of landfill gas emissions are based on modeled projections rather than on-site measurements, which could lead to inaccuracies if the waste composition varies significantly. Second, the calculation of solar exposure utilizes regional averages and does not consider the microclimate effects introduced by the landfill terrain. Thirdly the SWOT analysis although confirmed by experts, includes some degree of qualitative bias in expert opinion evaluation Subsequent research should integrate real-time gas monitoring solutions and localized environmental data collection to enhance precision.

The results indicate that medium-sized Iranian cities such as Karaj may repurpose existing landfills into resource recovery centers. This transition is consistent with circular economy concepts and can simultaneously resolve several urban issues. Yet, viability requires suitable policy environments, sustainable funding structures, and acknowledgment of regional environmental limitations. This experience can be leveraged for replication across other Iranian cities contending with equivalent waste and energy security issues. Sustainable urban resilience necessitates comprehensive systems that encompass ecological, economic, and health factors. This is precisely the pragmatic, multi-beneficial approach that renewable energy at waste sites can provide, though it requires adaptation to specific site conditions, logistical constraints, and administrative resources. The incremental strategy proposed offers a viable framework that balances aspirational goals with practical implementation.

5 Conclusion

This study shows that the Halghe Darreh municipal landfill in Karaj has significant and currently underused capacity to function as a renewable energy and public-health intervention site. Integrated landfill gas recovery and solar photovoltaic deployment could generate more than 55,000 MWh of electricity annually, substantially reduce methane emissions, improve local air quality, and lower population exposure to harmful pollutants. The SWOT analysis indicates that existing gas infrastructure, favorable site conditions, proximity to the power grid, and supportive national power-purchase mechanisms outweigh key barriers such as high upfront costs, dust-related efficiency losses, policy instability, and permitting delays. Importantly, these challenges are not unique to Karaj and have been effectively addressed in comparable national and international contexts through phased implementation, technical adaptation, and institutional coordination.

From a policy perspective, the findings position landfill-based renewable energy as a cost-effective, health-protective strategy aligned with circular economy and sustainable urban development objectives. A phased approach, beginning with small-scale landfill gas projects to achieve rapid emissions and air-quality gains, followed by solar deployment on capped landfill areas, offers a pragmatic pathway that limits financial risk while building municipal capacity. Public–private partnerships, stable regulatory frameworks, and targeted incentives are essential to ensure feasibility and scalability. Beyond energy production, the public health co-benefits strengthen the case for prioritizing such projects within municipal and national planning agendas. The Halghe Darreh experience provides a transferable model for other medium-sized Iranian cities seeking integrated solutions to waste management, energy security, and environmental health challenges.

Declarations

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Artificial Intelligence Disclosure

The authors confirm that AI-assisted tools were employed solely for language refinement and grammatical verification. Specifically, QuillBot (version 4) was used for textual restructuring, and Grammarly was utilized exclusively for grammatical accuracy checks. All content creation, data analysis, interpretation, and scientific conclusions were developed independently by the authors without AI generation. The final manuscript underwent rigorous human review to ensure academic integrity and scientific accuracy.

Authors' Contributions

All authors contributed equally to the conceptualization, methodology, data analysis, and manuscript preparation. Specifically, Fariba Jalali led the quantitative energy calculations and literature review; Mahnaz Jadidi coordinated the SWOT analysis framework and qualitative data collection; Mohammad Mosayyebi managed data acquisition from municipal sources and policy analysis; and Armita Mansouri[4] and Zeinab Atash Zaban[5] contributed to data interpretation and manuscript writing.

Availability of Data and Materials

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare no conflict of interest regarding the publication of this article.

Consent for Publication

Not applicable.

Ethical Considerations

This study complies with all applicable ethical standards. The research involved only publicly available data and official organizational reports, with no human or animal subjects involved. All data sources have been properly cited and acknowledged.

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