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Economic Feasibility of Using Municipal Solid Waste and Date Palm Waste for Clean Energy Production in Qatar

Ahmad Mohamed S. H. Al-Moftah [1,2], Mohammad Alnajideen [1,*], Fatima Alafifi [3,4], Pawel Czyzewski [5], Hao Shi [1,6], Mohammad Alherbawi [3], Rukshan Navaratne [1] and Agustin Valera-Medina [1]

1 College of Physical Sciences and Engineering, Cardiff University, Cardiff CF24 3AA, UK
2 Qatar National Research Fund (QNRF), Qatar Foundation, Doha P.O. Box 5825, Qatar
3 College of Science and Engineering, Hamad Bin Khalifa University, Doha P.O. Box 5825, Qatar
4 Qatar Environment and Energy Research Institute, Hamad Bin Khalifa University, Doha P.O. Box 5825, Qatar
5 Institute of Thermal Engineering, Poznan University of Technology, 60-965 Poznan, Poland
6 The Institute of Reactive Flows and Diagnostics, Technical University of Darmstadt, 64287 Darmstadt, Germany
* Correspondence: alnajideenmi@cardiff.ac.uk

Abstract: The transition to clean energy is crucial for mitigating the impacts of climate change and achieving sustainable development. Reliance on fossil fuels, which are integral to manufacturing and transportation, remains a major contributor to greenhouse gas (GHG) emissions. Biomass gasification presents a renewable energy alternative that can significantly reduce emissions. However, proper disposal of municipal solid waste (MSW) and agricultural residues, such as date palm waste (DPW), is an increasing global challenge, including in Qatar. This study evaluates the economic feasibility of implementing an MSW and DPW gasification plant for clean electricity generation in Qatar. The country's growing population and economic development have led to substantial waste production, making it an ideal location for waste-to-energy (WTE) initiatives. Using discounted cash flow (DCF) analysis, the study estimates the capital cost of a 373 MW_{th} facility at approximately \$12.07 million, with annual operating costs of about \$4.09 million and revenue of \$26.88 million in 2023. The results indicate a net present value (NPV) of \$245.77 million, a return on investment (ROI) of 84.80%, a payback period of approximately 5 years over a 20-year project lifetime and a net reduction of 206,786 tonnes CO_2 annually. These findings demonstrate the economic viability of biomass gasification in Qatar while contributing to reduced GHG emissions and advancing the country's sustainability goals under Qatar National Vision 2030.

Keywords: biomass gasification; municipal solid waste; date palm waste; economic feasibility; Qatar National Vision 2030

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1. Introduction

Decarbonising power and transport sectors necessitates reducing reliance on fossil fuels and transitioning to clean, renewable energy sources that produce nearly zero carbon emissions. This ambition has been championed by international agreements like the Paris Agreement and efforts under the United Nations Framework Convention on Climate Change [1–3]. The urgency of achieving net-zero emissions by 2050 was reaffirmed during the COP28 summit in 2023 [3–5]. However, transitioning to clean energy sources presents significant challenges, including maintaining stable and affordable energy supplies, fostering economic growth, and ensuring universal energy access [6,7].

Amongst the sustainable approaches, adopting low-carbon energy alternatives, such as replacing natural gas with bioenergy fuels like bio-methane for heating and electricity production, has gained prominence. Bioenergy, derived from biomass, encompasses a wide range of organic materials, including crop residues, agricultural waste, and industrial by-products [8]. Its diverse applications include bio-jet kerosene for air travel, liquid biofuel for road transport, and fuels for industrial processes and electricity generation [9]. As a renewable energy source, biomass has significant potential to reduce harmful emissions [10].

Globally, bioenergy constitutes 55% of renewable energy use and 6% of the global energy supply [11,12]. In 2023, electricity generated from bioenergy is reached nearly 750 TWh and is projected to increase to approximately 1350 TWh by 2030, meeting around 3.5% of global electricity demand [12]. While bioenergy plays a vital role globally, its integration into waste management practices presents unique opportunities, particularly in regions with significant waste generation. Solid waste, for instance, reached approximately 2.24 billion tonnes globally in 2022, equating to 0.79 kg per person per day [13]. The World Bank estimates that solid waste will increase by 73% to 3.88 billion tonnes by 2050, driven by rapid population growth and urbanisation [13].

In Qatar, a nation heavily reliant on fossil fuels, more than 2.5 million tonnes of municipal solid waste (MSW) are generated annually [14,15]. This waste, comprising agricultural residues, animal waste, and household organic material, predominantly ends up in landfills, contributing to air and water pollution through the emission of methane (CH_4), carbon dioxide (CO_2), and other harmful gases [16,17]. While these challenges are significant, Qatar's large-scale production of MSW and date palm waste (DPW) offers a substantial opportunity to adopt waste-to-energy (WTE) technologies. These issues are not unique to Qatar; in the broader Middle East and North Africa (MENA) region, urban waste exceeds 150 million tonnes annually [14].

Sweden is among the global leaders in WTE and waste management, having successfully utilised gasification technology to significantly reduce landfilling and emissions. For instance, the GoBiGas project [18], conducted in Gothenburg, exemplifies this approach by converting biomass and waste into syngas. The syngas is then processed into bio-methane, which can be used for heating and as a fuel source. In addition, Sweden has achieved remarkable success in waste management, with only 1% of its MSW ending up in landfills [19]. This waste is utilised in gasification technology, which generates clean energy from resources that cannot be recycled, thereby reducing emissions. Sweden's GoBiGas project serves as an excellent example of how landfill waste can be minimised through a combination of WTE, recycling, composting, and the recovery of materials and energy. These efforts have resulted in lower greenhouse gas (GHG) emissions, reduced reliance on fossil fuels, and increased use of clean energy sources within the country [18]. The amounts and share of waste deposited in landfills across Europe are presented by the European Environment Agency [19]. Qatar could adopt similar technologies to minimise landfill use and emissions, paving the way for a more sustainable future.

Besides MSW and agricultural residues, food waste from restaurants represents the third-largest contributor to landfills [20]. Landfills in Qatar and across the MENA region present environmental concerns, releasing CH_4, CO_2, and other gases such as ammonia (NH_3) [21], leading to soil degradation, groundwater pollution, and greenhouse gas emissions [22]. CH_4 and CO_2, which account for 90–98% of landfill gases, are the primary contributors to GHG pollution [23,24].

Qatar's economy has grown significantly, but one of its key challenges is the management of MSW [15]. A notable issue is the regular turnover of the expatriate community, which increases the waste stream and landfill pressures. The Ministry of Municipality and Environment faces the task of managing waste from various sources, highlighting the need for a detailed, integrated MSW management plan that addresses residential, industrial, construction, and commercial waste streams. One challenge of implementing biomass gasification technology in Qatar is the development of material recovery facilities (MRFs) that can separate MSW and produce solid fuels for gasification, such as Refuse-Derived Fuel (RDF) or Solid Recovered Fuel (SRF). Furthermore, constructing biorefineries for producing bioproducts, including biomaterials and biochemicals, is essential [15].

The use of MSW and DPW in Qatar for clean energy generation is particularly appealing, as it addresses the dual challenge of increasing energy needs and growing waste management issues. However, implementing such projects faces numerous obstacles and constraints, which can be categorised as technical, economic, social, political, and environmental. Technical barriers include the conditions and equipment required to process waste into energy, as well as the absence of proper waste segregation structures [23]. Economically, the establishment and operation of Waste-to-Energy (WTE) plants entail high costs, and there is a need for a stable policy regime to support these projects. Currently, Qatar lacks policies or incentives to attract private sector investment or collaboration in financing WTE projects [25,26]. Politically, the absence of clear backing increases uncertainty and risks, further hampering the pursuit and implementation of such initiatives.

To mitigate the above-mentioned impacts, the Qatari government has implemented programmes focused on increasing recycling and adopting sustainable waste management practices, such as WTE incineration and composting.

This study evaluates the feasibility of using a biomass plant to generate clean electricity from MSW and DPW through gasification in Qatar. This evaluation will determine whether this technology can be successfully implemented as a source of clean energy while assessing its economic and environmental impacts. The study also supports Qatar's National Vision 2030 and serves as a benchmark for neighbouring countries and regions with similar characteristics to evaluate the financial feasibility of adopting biomass gasification technology.

1.1. Energy Outlook

The State of Qatar, a small peninsular nation covering approximately 11.571 km^2, is located in the Middle East, bordered by Saudi Arabia and surrounded by the Arabian Gulf. Despite its small size, Qatar has a population of around 3 million people, with 72% residing in the capital city, Doha, one of the country's eight municipalities [27]. Qatar is well known for its high-income economy, primarily supported by oil and natural gas production, which contribute significantly to its status as one of the wealthiest nations globally. As a leading producer and exporter of natural gas and oil, Qatar plays a vital role in the global energy market [28,29]. However, in recent years, Qatar has made concerted efforts to diversify its energy sources, investing in renewable energy to reduce its dependence on fossil fuels and align with its national development vision [30].

Since 1965, Qatar has relied heavily on fossil fuels to meet its energy demands. By 2022, natural gas had become the dominant energy source, accounting for 87.3% of the country's energy mix, followed by oil at 12.6%. Renewable energy, while growing, still represented a small fraction at 0.1% [12,31]. This heavy reliance on fossil fuels has significantly contributed to the country's carbon footprint. Energy-related CO_2 emissions from Qatar accounted for 0.27% of global emissions, marking a 327% increase since 2000. This rise reflects the rapid industrial and economic growth in Qatar and highlights the urgent need to diversify energy sources to address environmental challenges [31].

Figure 1 provides an overview of key metrics related to Qatar's energy landscape, including total energy supply, production, consumption and CO_2 emissions. As of the most recent data [12,31], 99% of Qatar's electricity generation comes from natural gas, with a total electricity production reaching 54,623 GWh—a 498% increase since 2000. On a per capita basis, electricity consumption is 19.11 MWh, reflecting a 45% rise over the same period. The country's electricity generation is primarily powered by natural gas, with a peak demand of approximately 9000 MW and a total installed capacity exceeding 12,000 MW [32]. This rapid growth in electricity demand is largely driven by Qatar's rapid economic development and the need for air conditioning due to its hot climate. Electricity is priced at 0.10 Qatari Riyals (approximately 0.027 USD) per kWh, with the cost remaining consistent regardless of usage. However, the increasing demand for cooling is expected to drive future energy costs higher [15,33,34].

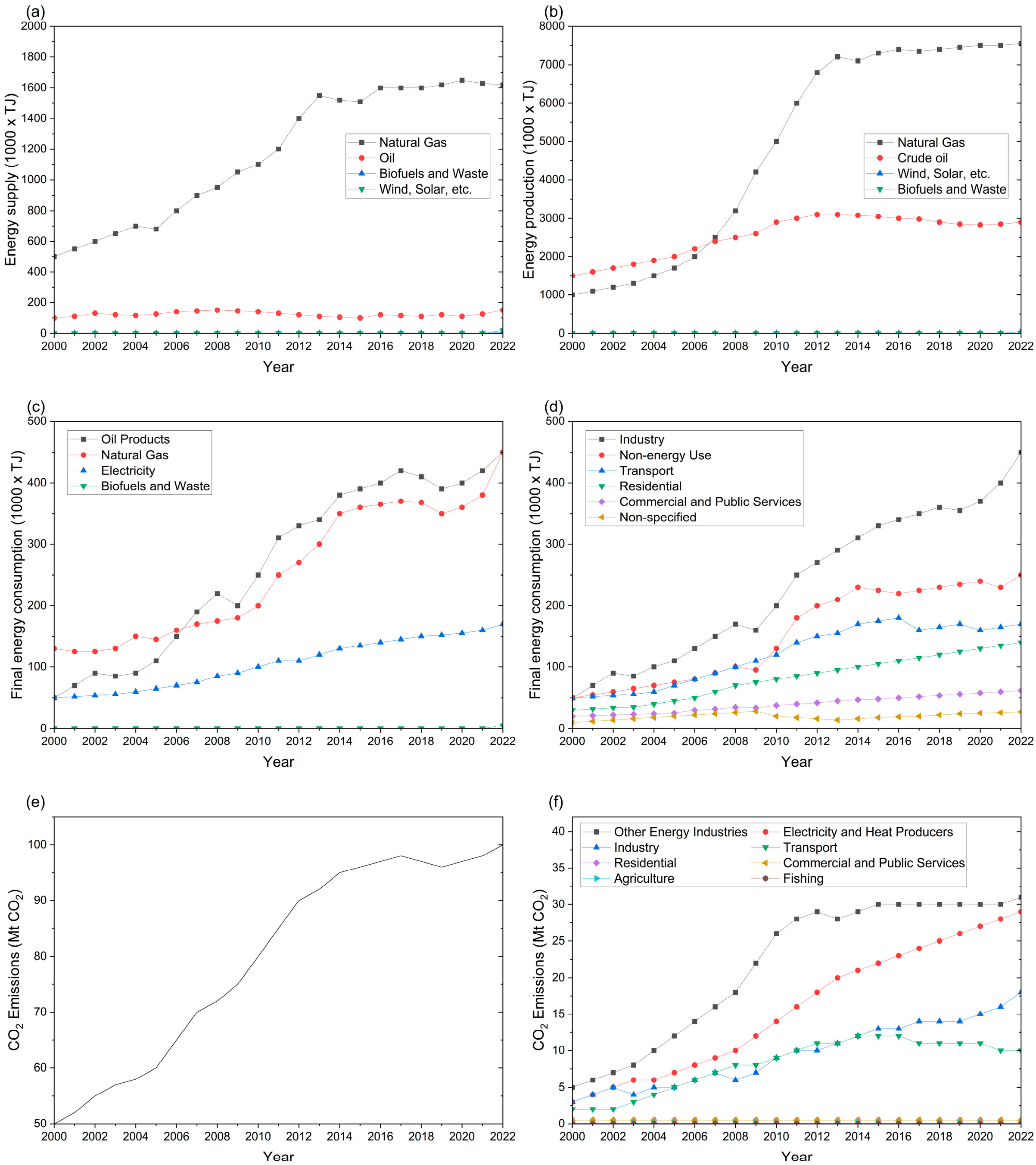

Figure 1. Qatar's key metrics for 2022; (**a**) total energy supply; (**b**) domestic energy production; (**c**) total final consumption by fuel source; (**d**) total final consumption by sector; (**e**) CO_2 emissions from fuel combustion; and (**f**) CO_2 emissions by sector. Data from [31], adjusted by authors.

In alignment with its national targets for environmental sustainability, Qatar implemented a carbon offsetting and mitigation framework during the FIFA World Cup Qatar

2022. This initiative supported the country's long-term energy goals by introducing low-carbon solutions such as energy-efficient stadiums powered by renewable energy sources, including solar power. The carbon-neutral approach also encompassed broader initiatives, such as renewable energy projects, forest conservation, and enhanced waste management systems that promote recycling and energy conservation [35–37]. These integrated strategies not only addressed the immediate environmental impacts of the tournament but also underscored Qatar's commitment to a more sustainable energy future.

Qatar's population growth, coupled with increasing urbanisation and industrialisation, has led to a significant surge in energy demand. For example, the Qatar General Electricity and Water Corporation (Kahramaa) reported a 10% growth in power consumption in 2019 alone [38]. In response to this growing demand and to mitigate its carbon footprint, Qatar has been making substantial investments in renewable energy. By 2030, the country aims to generate 20% of its electricity from renewable sources [39]. Key initiatives include solar power projects such as Al-Kharsaah, Mesaieed, Ras Laffan, and Dukhan, which are projected to produce around 4000 MW of electricity by 2030 [40,41]. These projects are expected to contribute 30% of Qatar's total power generation capacity and reduce CO_2 emissions by 4.7 million tonnes annually [39,42]. These efforts align with Qatar's broader objective of diversifying its energy mix, improving efficiency, and transitioning toward more sustainable energy solutions.

1.2. MSW and DPW in Qatar

1.2.1. Gasification Plant Statistics

Biomass conversion methods are broadly classified into thermochemical and biochemical processes. Thermochemical methods include gasification, carbonisation, pyrolysis, combustion, and catalytic liquefaction, whereas biochemical processes encompass anaerobic digestion and fermentation [25]. Both approaches break down feedstock molecules to produce biofuels, which can serve as renewable energy sources. Gasification converts carbon-based materials like MSW and DPW into syngas, a mixture of hydrogen, carbon monoxide, and methane [43]. This process offers a cleaner alternative to conventional waste disposal methods while generating energy.

Gasification is particularly suitable for Qatar as a means of producing clean energy from MSW and DPW. The country's climatic conditions result in waste with high moisture levels, particularly DPW, which poses challenges for conventional combustion processes. Gasification, however, can tolerate high moisture content and convert it into useful syngas, making it ideal for Qatar. The gasification process involves steps such as pyrolysis, partial oxidation, and gasification. In the pyrolysis stage, the waste material is thermally decomposed without oxygen to produce syngas with high levels of carbon monoxide, hydrogen, and methane. This syngas can subsequently be used in a gas turbine or processed through combined heat and power (CHP) systems to generate electricity [44]. MSW and DPW are high-calorific-value feedstocks that are abundantly available in Qatar, making them ideal for renewable energy production through gasification technology.

Qatar is actively exploring the gasification of MSW and DPW as a viable clean energy solution [45]. The adoption of gasification aligns with Qatar's National Vision 2030 [46], which aims to diversify the economy, reduce GHG emissions, and enhance environmental sustainability. Qatar National Vision 2030 outlines the country's long-term strategy for sustainable development, focusing on economic, social, human, and environmental pillars. It aims to transform Qatar into an advanced society capable of sustaining its development and providing a high standard of living for its people [47]. By 2030, it is estimated that gasification technology could supply 9.4% of Qatar's power consumption [48]. Waste-to-energy (WTE) projects, such as biomass gasification, provide Qatar with opportunities to enhance energy security and reduce its dependence on landfills. The gasification process breaks down waste materials in a low-oxygen environment to produce syngas, which can be used for electricity generation, heating, and industrial processes [49]. By-products such as tar and char from gasification can also be utilised in other industries, contributing to a circular economy.

The date palm is a vital cultural and economic asset in Qatar, producing various by-products, including leaflets, rachis, fruit stalk trimmings, and trunks, which are often discarded as waste. However, these by-products present significant opportunities for reuse, recycling, and energy recovery. Similarly, Qatar's MSW primarily consists of food scraps, yard waste, plastic, and paper. In 2023, the country generated over 2.5 million tonnes of MSW, as reported in the Qatar National Development Plan 2018–2022 [50,51].

Landfilling remains the predominant method of waste disposal, with approximately 95% of MSW ending up in landfills. This reliance on landfills poses environmental risks, including soil and water contamination, GHG emissions, and potential health hazards for nearby communities [52]. To address these challenges, Qatar has implemented the Qatar Integrated Waste Management Project (QIWMP), which includes landfill gas recovery, composting and recycling facilities, and a WTE plant to mitigate the environmental impact of MSW disposal [53].

Qatar's estimated 700,000 date palm trees produce approximately 26,000 metric tonnes of dates annually, with each tree generating around 250 kg of waste [54]. This results in an annual production of about 175,000 metric tonnes of DPW [55]. Although Qatar's date production is modest compared to regional producers like Saudi Arabia and Iran, leveraging DPW for energy recovery could significantly contribute to its National Vision 2030 [56,57]. Globally, the production of date palms has increased from 6.83 million metric tonnes in 2011 to 9.66 million metric tonnes in 2021 [58,59]. Qatar dedicates around 2598 hectares to date palm cultivation, with significant production in municipalities like Al-Rayyan, Umm Salal, Al-Khor, and Al-Shamal. Al-Rayyan alone accounts for 27% of national production, amounting to about 8419 tonnes annually, followed closely by Umm Salal and Al-Khor at 25.7% each. Al-Shamal contributes 21.6%, producing approximately 6735 tonnes annually across 561.3 hectares [60], as shown in Table 1.

Table 1. Municipalities and date palm statistics in Qatar [60].

Municipality (Region)	Date Palm (Number)	Production (Tonnes/Year)	Production (%)	Area (Hectare)
Al-Rayyan	175,396	8419.1	27.0	701.6
Umm Salal	166,951	8013.8	25.7	667.8
Al-Khor	166,951	8013.8	25.7	667.8
Al-Shamal	140,317	6735.0	21.6	561.3
Total	649,616	31,182	100	2598.5

At the pre-processing stage for WTE initiatives, MSW and DPW must undergo several key processes to optimise gasification efficiency. Waste collection, segregation, pre-treatment, transportation, and storage are critical steps in preparing feedstock for the gasification plant. Dedicated trucks and containers ensure waste is collected separately from residential, industrial, and agricultural sites, maintaining the integrity of the waste streams. Proper segregation at the source eliminates contaminants that could reduce the effectiveness of the gasification process. Collected waste undergoes pre-treatment, including shredding and grinding to reduce material size and sorting to remove non-combustible components [61,62]. These steps enhance the calorific value of the feedstock and improve gasification efficiency. Moisture reduction during pre-treatment is also crucial to optimise energy output. Once prepared, the feedstock is transported to the gasification plant, where storage facilities near the plant preserve the quality of the materials and prevent contamination. This systematic approach ensures the effective use of MSW and DPW for energy production, contributing to Qatar's efforts to achieve sustainable waste management and energy diversification [30].

1.2.2. Energy Production from MSW and DPW

According to Yayha et al. [53], a mature data palm tree produces approximately 20 kg of dry leaves annually. On average, an acre of land contains between 80 and 130 date palm trees. Each tree's trunk has an average mass of 60 kg, as shown in Table 2. In any given year, around 2–3 trees die per acre die and are replaced with newly planted ones. Currently, most of this waste is discarded in landfills, exacerbating pollution and contributing to CO_2 emissions.

Table 2. Energy potential and applications of DPW and MSW [63–65].

Waste Type	Weight (kg/Tree/Year)	Applications
Leaflets	9.2	Baskets, crates, carpets, food covers, fans etc.
Rachis	10.8	Timber, wood, furniture, mats, fuel etc.
Trunk	60.0	Poles, beams, girders, etc.
Fruit pruning	0.5	Cages, trays, cords, vases, twine etc.
Date stone	90.0	Medicinal usage, body temperature coolant etc.

To address this issue, various initiatives have been introduced to promote the utilisation of DPW for electricity generation and other purposes [66–69]. For instance, the Qatar National Research Fund, under the Qatar Foundation, has supported numerous studies investigating the potential of DPW for producing biofuels, biogas, and other valuable products [68,70]. Research by Sait et al. [71], employing thermogravimetric analysis (TGA), examined the thermochemical properties of date palm biomass. The study revealed that date palm seeds and leaves possess high calorific values and significant volatile content, making them well-suited for energy production. Specifically, the calorific value of date palm seeds was found to be 18.97 MJ/kg, while the leaves and trunk exhibited calorific values of 17.9 MJ/kg and 17.4 MJ/kg, respectively, as detailed in Table 3. This high energy potential highlights the promise of DPW as a bioenergy resource.

Table 3. DPW and MSW higher heating values (HHV) [15,71,72].

Residue Type	HHV ($MJkg^{-1}$)
Leaflets	17.9
Rachis	10.9
Trunk	17.4
Date stone	18.97
MSW	13.4

2. Methodology

2.1. Measurement of Total Residues

The residue-to-product ratio (RPR) is used to estimate the volume of residues generated by a tree or a particular area of land [71]. The RPR is typically derived from field data and adjusted to align with local conditions, such as climate, soil characteristics, and farming practices. In this study, both the RPR and the higher heating values (HHV) are actual measured values obtained from literature that represent climates similar to Qatar [44,73]. These values have been calculated based on global averages to ensure their applicability and reliability under the studied conditions.

The total date palm residue in Qatar, R_{Ti}, is calculated by multiplying the number of date palm trees in the country (649,616) by the average amount of residues each tree produces annually, as listed in Table 4. In 2021, Qatar produced over 2.5 million tonnes of MSW from commercial and household sources, equating to 1.6 kg of waste per capita per day [53].

Table 4. Estimation of total date palm residues in Qatar [53].

Residue Type	Residue Weight (kg/Tree/Year)	Number of Date Palm Trees	Total Residues (kg × 10^6/Year)
Leaf	9.2	649,616	5.976
Rachis	10.8	649,616	7.015
Trunks	60.0	649,616	38.967
Date stone	90.0	649,616	58.465

2.2. Total Potential Energy

Based on the findings by Hiloidhari et al. [74] and Tolessa [75], the gross crop residue potential ($GCRP$) is calculated using factors such as the area under cultivation, the amount of crop produced, and the residue-to-product ratio (RPR), as given by Equation (1):

$$GCRP = \sum_{i=1}^{t} CA_{(i)} \times CY_{(i)} \times RPR_{(i)} \quad (1)$$

where; $GCRP$ is the potential of gross crop residue, t represents the total number of crops (tonnes), $CA_{(i)}$ is the cultivated area of the i^{th} crop (hectares), $CY_{(i)}$ is the crop yield of the i^{th} crop (hectares), and $RPR_{(i)}$ is the residue-to-product ratio of the i^{th} crop.

For date palm trees, Equation (1) can be rewritten as:

$$GCRP = \sum_{i=1}^{t} RA_{(i)} HHV_{(i)} \quad (2)$$

where; $RA(i)$ represents the quantity of available residues from the i^{th} crop per hectare per year (in MJ/year) and $HHV(i)$ is the high heating value (in MJ/kg).

Using Equation (2), the total energy potential of date palm residues in Qatar is calculated based on the weight of the residues and their respective high heating values.

The capital cost of the power plant is calculated using the following scaling Equation (3) [76]:

$$C_b = C_r \left(\frac{S}{S_r} \right)^n \quad (3)$$

where; C_b is the estimated capital cost of the new power plant (in 2016), C_r is the reference plant capital cost, S is the capacity of the new power plant, S_r is the reference plant capacity, and n is the standard scaling factor of 0.6, obtained from historical data for similar-scale economic analysis [73]. It was chosen based on the work of (Tribe, M.A. and Alpine, R.L.W., 1986) [77]. This selection was influenced by various factors, including technological constraints, economic feasibility, environmental sustainability, and regulatory requirements.

To adjust for inflation to 2023, Equation (4) is used:

$$\frac{C_a}{C_b} = \frac{I_a}{I_b} \quad (4)$$

where C_a and C_b represent the estimated capital costs of the new plant in 2023 and 2016, respectively. l_a and l_b are the chemical engineering plant cost indices for 2023 and 2016, respectively. Therefore, we can derive:

$$\frac{C_{2023}}{C_{2016}} = \frac{l_{2023}}{l_{2016}} \tag{5}$$

Rearrange Equation (5):

$$C_a = C_{2023} = \frac{l_{2023}}{l_{2016}} \times C_{2016} \tag{6}$$

$$\text{Biomass cost} = \text{Collection cost} + \text{Storage cost} + \text{Transportation cost} \tag{7}$$

$$\text{Operating cost} = \text{Fixed cost (inclusive of biomass cost)} + \text{Variable cost} \tag{8}$$

To assess the project's financial viability, discounted cash flow (DCF) analysis is used to calculate the Net Present Value (NPV), as given by Equation (9) [74]:

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \tag{9}$$

where Ct is net cash flow over the year, i is the financial discount rate, N is the total number of years and t is the time of the cash flow. The Return on Investment (ROI) for a power plant with an operating life of 20 years in Qatar can be calculated using Equation (10) [76]:

$$ROI = \frac{\mathrm{P} \times (1 - \mathrm{TR})}{(\mathrm{TPC} \times \mathrm{CRF} + \mathrm{TVC})} \tag{10}$$

where; P is the profit, TR is the tax rate (10% for Qatar), TPC is the total plant cost, CRF is the capital recovery factor, and TVC is the total variable cost. It is worth noting that the typical operating time of a power plant is much longer than 20 years. However, for market reasons, i.e., a satisfactory rate of return for investors, a period of 20 years is conducive to acquiring them. Moreover, after 20 years, significant modernisation investments may be necessary, changing the investment balance. CRF can be found in Equation (11):

$$CRF = \frac{i}{1 - (1-i)^{-n}} \tag{11}$$

The payback period can be calculated using Equation (12) [78]:

$$Payback\ Period = Y + \frac{N}{P} \tag{12}$$

where; Y is the last year with negative cumulative NPV, N is the absolute value of the negative cumulative NPV at the end of the year, and P is the annual cash flow during the year after Y.

3. Results and Discussions

3.1. Qatar's Energy Potential from DPW and MSW

The total energy potential of date palm residues in Qatar is summarised in Table 5. The total residues were calculated by multiplying residues weight by the number of date palm trees (see Table 4), while the total energy was calculated by multiplying the higher heating value (HHV) by the total residues, as given in Sections 2.1 and 2.2. The data shows that date stones have the highest energy potential among the residues, contributing a total energy of 1.109×10^9 MJ. Trunks follow as the second-largest contributor, providing

0.678×10^9 MJ. Leaflets contribute 0.106×10^9 MJ, while rachis residues account for the lowest contribution at 76.46×10^9 MJ. MSW in Qatar contributes 33.4×10^6 MJ to the total energy potential. The combined total energy potential of DPW and MSW reaches 2.01×10^9 MJ annually, demonstrating the significant renewable energy resource represented by these waste streams.

Table 5. Total energy of date palm residue and MSW in Qatar.

Type of Residue	Total Residues (kg $\times 10^6$ /year)	HHV (MJ/kg)	Total Energy (MJ $\times 10^6$)
Leaflets	5.976	17.90	106.97
Rachis	7.015	10.90	76.46
Trunks	38.967	17.41	678.42
Date stone	58.465	18.97	1109.08
MSW	2.5000	13.40	33.40
Total	112.923		2004.43

Biomass HHV, such as trunks and date stones, is influenced by moisture content, chemical composition (cellulose, hemicellulose, lignin, ash, and oil), and environmental factors [79]. The type of biomass residues, such as trunks or date stones, also impacts variations in energy potential. When evaluating HHV, it is essential to consider not only the material's inherent composition but also the drying and storage processes that affect moisture content [71]. The HHV serves as an indicator of the energy content of residues from DPW, as well as MSW available in Qatar. Consequently, the coefficients of variation for these residues are affected by factors including chemical identity, the amount of water-soluble compounds, and the polymerisation of organic substances present in the residues.

In general, the HHV values for trunks and date stones are higher than those for leaflets and rachis due to the former's higher carbon content and lower hydrogen content [71]. Moisture content is a key factor significantly affecting HHV differences. A direct relationship has been observed: higher moisture content correlates with lower HHV, as part of the energy content is used to vaporise the water [80,81]. For instance, the HHV of trunks (see Table 5) is approximately 17.41 MJ/kg, while for date stones, it is 18.97 MJ/kg. This disparity is attributed to the lower moisture content in date stones compared to trunks.

It is worth mentioning that, for the majority of the year, the climate of Qatar is classified as dry due to low relative air humidity [82]. This, coupled with high temperatures, significantly facilitates the drying process of biomass, including trunks and date stones. Compared to the climatic conditions of European countries such as Sweden, where natural drying of biomass can take several years, Qatar's climate provides a considerable advantage. This natural drying capability reduces the cost of biomass conditioning required for thermochemical conversion processes such as gasification and combustion.

3.2. Economic Analysis

In this study, the economic analysis of biomass gasification was conducted using the discounted cash flow (DCF) methodology. This approach estimates the project's future cash flows, discounts them to their present value, and determines the net present value (NPV). By accounting for the time value of money, the DFC method provides a comprehensive evaluation of the project's financial viability.

3.2.1. Capital Costs

The initial capital cost represents the total expense required to install the project, including power plant construction, auxiliary systems (e.g., transformers, evacuation lines), and all upfront costs necessary for development construction, and commissioning [74,83].

These costs typically include land acquisition, equipment and materials procurement, legal and regulatory fees, labour, construction, and associated engineering and design fees.

This study estimates costs for a 373 MW_{th} gasification-based biomass electricity generation facility, processing MSW and DPW. The plant configuration includes a single steam generator, condensing steam turbine, biomass storage and handling systems, and a post-emissions control system. The operational specifications of the facility include the reception, storage, and gasification of MSW and DPW with moisture content ranging between 20% and 50% [84]. It is worth noting that the 373 MW_{th} capacity for the biomass gasification plant proposed in this study represents a mid-sized, economically viable facility capable of efficiently managing substantial feedstock volumes while aligning with regional energy and resource availability.

To estimate costs, the Chemical Engineering Plant Cost Index (CEPCI) is employed. This index provides cost projections for chemical process industries, including equipment, construction labour, engineering processes, and supervision activities [85]. The CEPCI values for 2016 and 2023 are $541.7 and $808.7, respectively [85]. The facility is designed to start up using either natural gas or diesel fuel. Considering local conditions in Qatar, such as biomass production and treatment costs, the average capital cost is estimated at $3669/kW [84]. For a nominal capacity of 112 MW_e (373 MW_{th}), the total estimated capital cost of the power plant is $183,450,000 [84]. By applying Equations (3)–(6), the capital cost of the power plant ($C_{b,2016}$) in 2016 is $8,083,008.04, while the estimated cost for a 373 MW_{th} biomass power plant in 2023 ($C_{b,2023}$) is $12,067,064.06.

3.2.2. Operating Cost

The operating cost of the biomass gasification facility includes expenditures for biomass feedstock, labour, maintenance, and other operational expenses. These costs are influenced by system availability and the biomass consumption rate. Using the exponential method, the fixed cost is estimated at $110/kW annually based on 2016 values, while the variable cost is calculated as $4.2/MWh. Additional operational costs include the collection, storage, and transportation of biomass feedstock to Qatar's Dukhan biomass plant, with an average transportation distance of 150 km. The transportation cost is estimated at $100 per 9 tonnes, while collection and storage costs are $80 and $25 per 9 tonnes, respectively [76]. Using Equations (3) and (6), the fixed cost for a 373 MW_{th} biomass power plant in 2023 is $263,113.96, and the variable cost amounts to $1,251,022.58. Furthermore, the biomass process cost, calculated using Equation (7), is $2,572,135. Combining these expenditures, the total operating cost of the biomass power plant, using Equation (8), is $4,086,271.54.

The cost of biomass feedstock required to supply the power plant is also considered in the operating expenses. It is important to note that the proposed facility would be pioneering in nature, providing a real database for calculating and designing subsequent biomass energy investments in Qatar [86]. At present, biomass pricing in Qatar remains predictive. However, due to the waste-derived nature of biomass in the country, its price is expected to be lower than global market prices [68]. Potential suppliers may view the facility as an effective disposal site for post-production waste, further reducing costs. It is essential to note that the analysed residues, while suitable for energy production, could also have alternative applications, potentially impacting their availability and pricing as energy carriers [87,88]. However, Qatar's uniform energy and industrial structure–primarily based on oil and gas–along with its geographic isolation from global biomass waste markets, minimise the likelihood of such price pressures [89,90]. Consequently, the steady and wide availability of the analysed biomass types can be anticipated for the facility, ensuring a reliable and cost-effective feedstock supply for energy production.

3.2.3. Revenue and Cash Flow

In the electricity sector, the primary source of revenue comes from selling generated power to the distribution grid, as illustrated in Figure 2. Revenue is determined by the electricity price and the plant's capacity factor. In this study, the biomass plant operates with an electricity generation efficiency of 30%, with an average capacity factor of 0.8, and an average electricity price of \$30/MWh [83]. The facility, rated at 373 MW_{th} and generating 112 MW_e of power, is expected to maintain consistent annual sales revenue. The annual revenue can be calculated as follows [73]:

$$\text{Annual Revenue} = 112\ \text{MW}_e \times 8000\ \text{h/year} \times \$30/\text{MWh} = \$26{,}880{,}000 \tag{13}$$

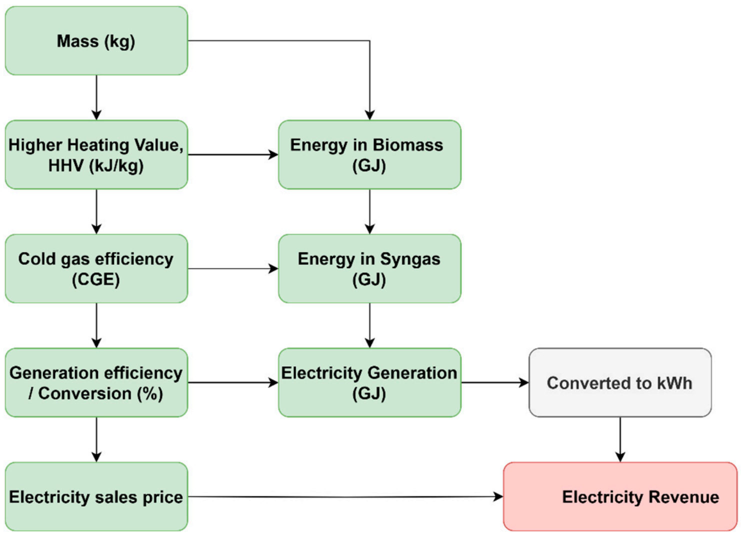

Figure 2. Sales revenue computation for MSW and DPW gasification power plant. Adjusted from [73].

This calculation assumes stable operation of the plant under the given capacity factor and electricity price conditions.

The discounted cash flow (DCF) method is employed to assess the financial feasibility of the biomass gasification plant. The DCF analysis calculates key financial metrics, including the net present value (NPV), return on investment (ROI), and payback period. The total investment for the biomass plant comprises the capital cost and operating cost, amounting to \$16,153,335.6. Additional costs include the working capital cost, which is estimated at 15% of the total investment, equalling \$2,243,000.34 [91]. The decommissioning cost of the plant is approximately \$2,900,000 [78]. The average inflation rate in Qatar is reported at 1.47% [92], and the expected completion period for the plant is two years. Given Qatar's structural financing policies and commitment to renewable energy, it is assumed that the project will be self-financed. This approach eliminates the need for debt servicing costs, which are often included in operating expenses under alternative financing scenarios. Assuming a discount rate of 8% and a project lifetime of 20 years, the NPV of the biomass gasification power plant is calculated using Equation (9) [76]. The resulting NPV is \$245,765,864.05.

Figure 3 illustrates the projected cash flow over the plant's 20-year operational period, highlighting the NPV derived from the relationship between operating costs and revenue. The NPV shown in Figure 3 exhibits high values starting after the first two years, reflecting the commencement of operations for the MSW and DPW gasification plant. This trend indicates a positive economic outlook, as revenue inflows progressively outweigh operating cost outflows over the project's lifetime. The widening gap between the positive inflows (revenue) and negative outflows (operating costs) underscores the plant's ability to generate significant surplus revenue in the long run.

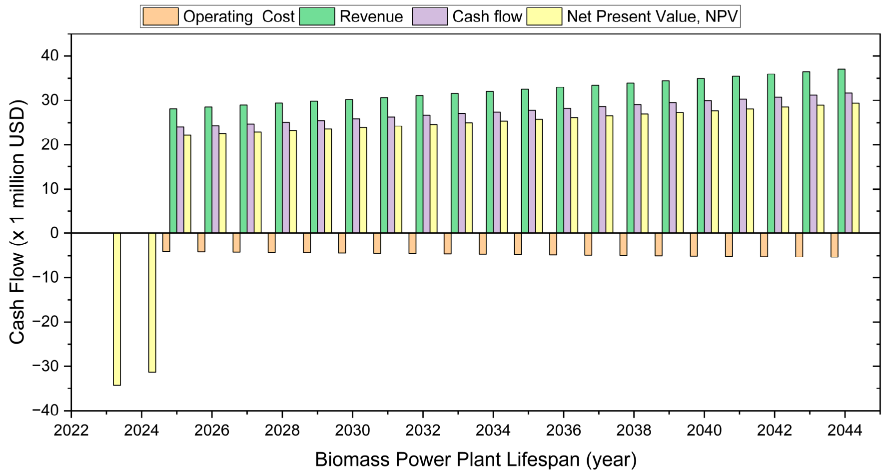

Figure 3. Projected cash flow over 20 years of biomass gasification plant operation in Qatar.

The capital recovery factor (CRF), estimated using Equation (11), was found to be 0.1. Additionally, the return on investment (ROI) is calculated using Equation (10), which considers the total revenue return and the CRF, applying a discount rate of 8% and a plant lifetime of 20 years. The results are depicted in Figure 4, which demonstrates the ROI progression and further highlights the plant's financial feasibility and profitability under the assumed conditions.

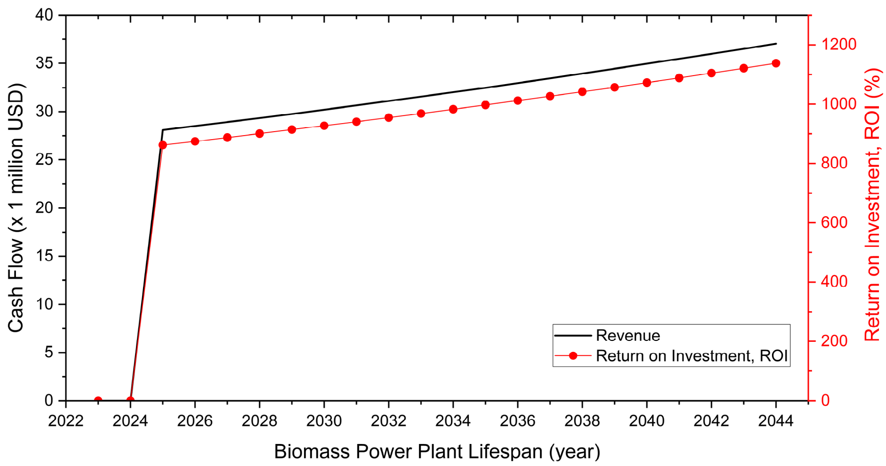

Figure 4. Return on investment, ROI, of the plant operation over 20 years.

The return on investment (ROI) is projected to increase annually over the plant's lifetime, aligning with the revenue growth. The calculated ROI for the biomass gasification power plant is 84.78%, which indicates that for every dollar invested (USD, $), the project is expected to generate a return of 84.78 cents over its operational lifetime. The combination of a high NPV and significant ROI underscores the financial feasibility of the biomass gasification power plant in Qatar. These results also highlight the project's strong potential to deliver long-term economic benefits and contribute to the country's renewable energy initiatives.

The payback period for the biomass gasification plant is estimated using Equation (12) and is found to be approximately 5 years, as illustrated by the intersection point in Figure 5. This intersection represents the moment when the total investment is fully recovered through accumulated profits. Furthermore, the cumulative NPV grows at a significantly faster rate than the annualised NPV due to the effect of compounded profits over time. This results in intersecting plots, where the intersection highlights the point at which accumulated annual profits equal the initial investment. The rapid growth of cumulative NPV and the relatively short payback period further emphasise the plant's high-profit potential and its strong financial viability.

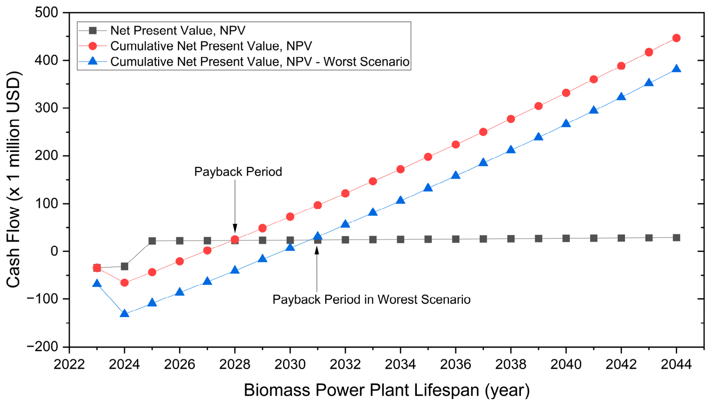

Figure 5. Overview of financial indicators: NPV as a function of power plant lifetime and payback period.

Examples from other countries suggest that for thermal power plants, actual investment costs can substantially surpass initial estimates, sometimes by as much as 300% for nuclear facilities [93]. For facilities utilising fuels such as biomass or coal, cost overruns are generally less extreme but remain common.

The proposed biomass gasification project in Qatar demonstrates promising economic metrics, including a total capital cost of $12.07 million ($3669/kW), annual operational costs of $4.09 million, and an expected revenue of $26.88 million annually. The plant achieves a net present value (NPV) of $245.77 million, a return on investment (ROI) of 84.80%, and a payback period of 5 years. To ensure a fair comparison, power plants must share similar capacities, technologies, processes, and environmental conditions. However, as an illustrative example here is; a biomass gasification project in Portugal, with a capacity of 11 MW, relies on forestry residues as feedstock [78]. The project's capital cost is €2500/kW ($2800/kW at 2019 exchange rates), with an NPV of €2.367 million, an internal rate of return (IRR) of 8.66%, and a payback period of 23 years [78]. The Portuguese project faces challenges such as high feedstock transportation costs and lower plant efficiency due to climatic and logistical constraints. While both plants achieve a 30% efficiency in electricity conversion, Qatar's dry climate reduces biomass drying costs, enhancing operational profitability compared to wetter regions like Portugal. Qatar's project offers economic viability, making it an attractive model for waste-to-energy initiatives in the MENA region.

For analysis of the given data, it is assumed that the biomass power plant in Qatar operates at an efficiency of 30% for electricity generation. This efficiency rate is critical in evaluating the viability and success of the project, as it directly influences revenue, operational costs, and the overall profitability of the plant. The amount of energy produced from biomass depends on factors such as the type of biomass resource utilised, the plant layout, and the methods employed during operations [94]. One empirical example is the biomass power plant in Copenhagen, Denmark, where the conversion efficiency is also 30% [95]. This plant uses both straw and wood waste as feedstocks to generate electricity. Similarly, a review of Alkhathami (2022) [73] and related literature indicates [16,96–98] that a 30% efficiency rate is a realistic assumption for the biomass power plant, which utilises MSW and DPW as feedstocks.

In this study, a worst-case scenario assumes investment cost overruns of up to two times the original estimate. This assumption has been incorporated into the profitability calculations and reflected in Figure 5. Even under this scenario, the estimated payback period extends to approximately 8 years, which remains a highly favourable value for this type of investment. This result further highlights the project's resilience and economic feasibility, even under less optimal conditions.

3.2.4. Emissions

The implementation of the MSW and DPW gasification plant offers a significant reduction in carbon emissions. The gasification process prevents the release of methane (CH_4) and carbon dioxide (CO_2), which are typically emitted from decomposing waste in landfills. Methane, with a global warming potential (GWP) of 28–34 times that of CO_2, represents a critical emission to mitigate. The avoidance of 72,500 tonnes of CO_2-equivalent emissions annually highlights the environmental advantage of this approach.

The electricity generated by the plant, approximately 896,000 MWh annually, replaces natural gas-based electricity, avoiding an estimated 358,400 tonnes of CO_2 emissions each year. While the plant generates emissions during syngas combustion and through operational activities such as transportation and pre-treatment, these are relatively modest. Total emissions from the gasification process amount to approximately 224,114 tonnes of CO_2 annually.

By balancing avoided emissions against generated emissions, the gasification plant achieves a net reduction of 206,786 tonnes of CO_2 annually. This result highlights the plant's role as a cleaner alternative to landfill disposal and fossil fuel-based energy production, contributing significantly to Qatar's National Vision 2030. Table 6 provides a breakdown of carbon footprint calculations, and further details are available in the Appendix A.

An annual net reduction of 206,786 tonnes of CO_2 represents approximately 0.2% of Qatar's total CO_2 emissions. According to data from the International Energy Agency (IEA) [99], Qatar's CO_2 emissions from fuel combustion were approximately 90.667 million tonnes in 2022. While this percentage may seem modest, it is a meaningful step towards mitigating climate change. Every reduction contributes to the global effort to lower greenhouse gas concentrations in the atmosphere. Moreover, implementing measures that achieve such reductions can set a precedent for further environmental initiatives, potentially leading to more substantial decreases in emissions over time.

Table 6. Carbon footprint calculation for MSW and DPW gasification [33,53,71,74,100]. The detailed calculations are available in the Appendix A.

	Source	Calculation Assumptions	Result (Tonnes CO_2/Year)
Carbon emissions from current practices	Methane from landfills	2.50 million tonnes MSW/year, 1 kg CH_4/tonne, GWP = 28–34	70,000 (CO_2-eq from CH_4)
	CO_2 from landfills	1:1 ratio with CH_4	2500 (CO_2 from landfills)
	Total landfill emissions avoided.	CH_4 + CO_2	72,500
	Fossil fuel displacement	896,000 MWh electricity, 0.4 tonnes CO_2/MWh	358,400
Emissions from biomass gasification	Syngas Combustion	112.9 M kg feedstock, 50% carbon, 1 tonne C = 3.67 CO_2	207,176
	Transportation	150 km, 100 kg CO_2/tonne	11,292
	Pre-treatment Operations	0.05 tonnes CO_2/tonne	5646
	Total Gasification Emissions	Syngas + Transportation + Pre-treatment	224,114

Category	Result (Tonnes CO_2/year)
Total Avoided Emissions	430,900
Total Gasification Emissions	224,114
Net Carbon Reduction	206,786

4. Conclusions

The gasification of municipal solid waste (MSW) and date palm waste (DPW) offers a sustainable and economically viable solution to Qatar's waste management challenges.

This study demonstrates that the proposed biomass gasification plant can effectively reduce landfill dependency while generating clean energy, thereby contributing significantly to Qatar's National Vision 2030.

Qatar generates approximately 2.5 million tonnes of MSW annually, a figure projected to rise to 4.4 million tonnes by 2023, according to the Ministry of Municipality and Environment. This feasibility study estimates that the capital cost of a 373 MW_{th} biomass gasification power plant in 2023 is $12.07 million, with fixed operating costs of $263.11 million and variable costs of $1.25 million. The total cost for the collection, transportation, and storage of MSW and DPW is estimated at $2.57 million, resulting in total annual operating costs of $4.09 million. The analysis further reveals a net present value (NPV) of $245.77 million and an annual revenue of $26.88 million, with a payback period of approximately 5 years. Additionally, the gasification plant achieves a net reduction of 206,786 tonnes of CO_2 annually.

This study also highlights critical challenges to implementing MSW and DPW gasification, such as ensuring sufficient feedstock availability and managing the costs of collection, transportation, and pre-treatment. Despite these challenges, the results underline the potential for scalability and replication of this technology in Qatar and other regions with similar waste profiles.

Future research should focus on exploring the co-gasification of MSW with other waste streams, utilising syngas, produced during gasification, for gas turbine power generation, assessing applications for by-products, investigating additional strategies for reducing carbon footprints, and optimising process efficiencies to enhance economic and environmental outcomes. Addressing these areas will enable the proposed technology to play an even greater role in advancing Qatar's renewable energy objectives and reducing greenhouse gas (GHG) emissions from conventional energy sources.

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Nomenclature

CEPCI	Chemical Engineering Plant Cost Index
CO_2	Carbon Dioxide
CRF	Capital Recovery Factor
DCF	Discounted Cash Flow
DPW	Date Palm Waste
GCRP	Potential of Produced Crop Residue
GHG	Greenhouse Gases
HHV	High Heating Value
kg	Kilogram
MSW	Municipal Solid Waste
MW_e	Megawatt electrical
MW_{th}	Megawatt thermal
NPV	Net Present Value
ROI	Return on Investment
USD	United States Dollar
WTE	Waste-to-Energy

Appendix A

Carbon Footprint Calculation for MSW and DPW Gasification [33,53,71,74,100].

1. Carbon Emissions from Current Practices

A. Methane (CH_4) and CO_2 Emissions from Landfills

- Annual MSW generation: 2.5 million tonnes
- CH_4 emission factor: Approx. 1 kg CH_4 per tonne of MSW/year (based on IPCC guidelines).
- Methane Global Warming Potential (GWP): 28–34 times more impactful than CO_2 over 100 years (IPCC AR6).
- Landfill gas composition: 50% CH_4, 50% CO_2 (by volume).

Calculation:
CH_4 emissions = 2.5 million tonnes MSW $\times$ 1 kg CH_4/tonne = 2500 tonnes CH_4.
CH_4 emissions in CO_2 equivalent = 2500 $\times$ 28 = 70,000 tonnes CO_2-eq/year.
CO_2 from landfill = Approx. 2500 tonnes/year (assuming a 1:1 ratio with CH_4).
Total landfill emissions: 72,500 tonnes CO_2-eq/year.

B. Avoided Emissions from Fossil Fuels

- Electricity generation potential: 373 MW_{th} plant with 30% efficiency = 112 MW_e.
- Displacement of natural gas: Approx. 0.4 tonnes CO_2/MWh for gas-based power.

Calculation:
Annual electricity generation = 112 MW $\times$ 8000 h = 896,000 MWh.
Avoided CO_2 emissions = 896,000 MWh $\times$ 0.4 tonnes CO_2/MWh = 358,400 tonnes CO_2/year.

2. Emissions from Biomass Gasification

A. Direct Emissions from Syngas Combustion

- The carbon content of MSW and DPW: Approximately. 50% by weight (literature value).
- Annual MSW and DPW usage: 112.9 million kg.
- Carbon to CO_2 conversion: 1-tonne carbon = 3.67 tonnes CO_2.

Calculation:

- Carbon content = 112.9 million kg × 50% = 56.45 million kg.
- CO_2 emissions = 56.45 × 3.67 = 207,176 tonnes CO_2/year.

B. Emissions from Transportation, Pre-treatment, and Operations

- Transportation: 150 km average distance; 100 kg CO_2/tonne (literature estimate).
- Pre-treatment energy use: Approx. 0.05 tonnes CO_2/tonne (based on similar studies).

Calculation:
Transportation emissions = 112,923 tonnes × 0.1 tonnes CO_2/tonne = 11,292 tonnes CO_2/year.
Pre-treatment emissions = 112,923 tonnes × 0.05 tonnes CO_2/tonne = 5646 tonnes CO_2/year.
Total operational emissions: 11,292 + 5646 = 16,938 tonnes CO_2/year.

C. Total Gasification Emissions:

Total emissions = 207,176 (syngas combustion) + 16,938 (operations) = 224,114 tonnes CO_2/year.

3. Calculate the Net Carbon Footprint

Net Emissions Saved:
Avoided landfill emissions: 72,500 tonnes CO_2-eq/year.
Avoided fossil fuel emissions: 358,400 tonnes CO_2/year.
Total avoided emissions: 430,900 tonnes CO_2/year.
Net Carbon Emissions from Gasification:
Total emissions: 224,114 tonnes CO_2/year.
Net Carbon Footprint Reduction:
Emissions saved − emissions generated = 430,900 − 224,114 = 206,786 tonnes CO_2/year.

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