# Techno-economic evaluation of a power-to-methane plant in Qatar: Levelized cost of methane, financial performance metrics, and sensitivity analysis

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Chemical Engineering Journal 471 (2023) 144725

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

# Techno-economic evaluation of a power-to-methane plant : Levelized cost of methane, financial performance metrics, and sensitivity analysis

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ARTICLE INFO

*Keywords:*
Renewable methane
Levelized cost of methane
Renewable energy transition
Technoeconomic analysis
Financial viability
Sensitivity analysis

ABSTRACT

This study presents a comprehensive techno-economic analysis of a power-to-methane plant, investigating its financial viability and profitability over 20 years. The financial performance of the plant is evaluated using key metrics such as net present value (NPV), internal rate of return (IRR), and levelized cost of methane (LCOM). The main findings reveal that under the current assumptions, the plant faces challenges in achieving financial viability, with a negative NPV of −$3,818,163 and an IRR of −1%, indicating a net loss over the 20 years and a lack of profitability for investors. The calculated LCOM is 1.75 $/kg, which provides an estimate of the cost to produce renewable methane from the plant. To further understand the conditions necessary for the plant to become financially viable, a sensitivity analysis is conducted, examining the effects of varying key parameters such as the selling price of methane, $CO_2$ costs, and discount rates. The sensitivity analysis demonstrates that the financial viability and profitability of the plant are highly sensitive to the selling price of methane, with the NPV turning positive and the IRR exceeding the break-even point at selling prices above $2.1/kg. Moreover, the analysis reveals that higher $CO_2$ costs lead to poorer financial performance, while lower discount rates result in a higher perceived value of the plant. In summary, the power-to-methane plant faces financial challenges under the current assumptions, but under certain conditions, it could become viable and profitable. The findings of this study provide valuable insights into the plant's potential market viability and can inform future decision-making processes and development strategies for power-to-methane technologies. It is recommended that additional research investigates the impact of technological advancements and integration with other renewable energy systems on the financial performance of the plant and their contribution to the transition to renewable energy systems.

## 1. Introduction

The demand for energy is anticipated to increase, and it has become increasingly challenging for governments and societies to meet this demand in a sustainable manner [1]. Renewable energy sources such as wind and hydropower are receiving increased consideration as possible solutions to this issue. These sources have several advantages over fossil fuels, including a reduction in greenhouse gas emissions, a decrease in air pollution, and an increase in energy security [2].

Power-to-methane is a promising pathway for capturing renewable energy sources for use in the energy sector. The pathway involves electrolyzing water with renewable electricity to produce hydrogen. The hydrogen is then combined with carbon dioxide to create renewable methane, a useful fuel that can be used for transportation, heating, and electricity generation, among other applications. The efficiency of the power-to-methane pathway depends on a number of factors, including the efficiency of the electrolysis and methanation processes as well as the renewable electricity source used to power the process. Temperature, pressure, and electrode material can all have an effect on electrolysis efficiency, and improvements in these areas can lead to greater electrolysis efficiency [3]. Furthermore, reaction conditions such as temperature, pressure, catalysts, and the hydrogen-to-carbon dioxide ratio can impact methanation efficiency [4]. Power-to-methane is considered extremely scalable, with applications ranging from small decentralized systems to large centralized power plants [5]. Power-to-methane is scalable because it can store and transport energy in the form of methane, a highly versatile fuel that can be used for a variety of applications, including electricity generation, transportation, and heating. One of the primary motivations for researching the power-to-methane pathway is its potential as a renewable energy storage

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https://doi.org/10.1016/j.cej.2023.144725
Received 6 April 2023; Received in revised form 8 June 2023; Accepted 8 July 2023
Available online 10 July 2023

solution [5]. Additionally, it has the potential to produce low-carbon fuels for the transportation sector, which is a major contributor to greenhouse gas emissions [6]. Likewise, the pathway can support the circular economy by utilizing waste carbon dioxide from industrial processes and other sources as feedstock for methane production [7]. Despite power-to-methane pathway having many advantages, there are a few key technical challenges that must be resolved prior to its large-scale implementation and economic viability. Improving the efficiency of the electrolysis process is one of the most significant challenges power-to-methane must overcome. Electrolysis is an energy-intensive process, and the process's efficiency has a direct impact on the overall efficiency and economics of the energy-to-methane pathway. The availability of carbon dioxide ($CO_2$) can also pose a challenge for power-to-methane. $CO_2$ concentrations in the atmosphere are typically low, making large-scale extraction difficult [8].

When evaluating the practical application of hydrogen generated through electrolysis, it is imperative to acknowledge various crucial elements that support the power-to-methane technique. Although hydrogen exhibits a high energy density per unit mass (120 MJ/kg), its energy density per unit volume is considerably lower (5.6 MJ/L at 700 bar). This particular characteristic of the substance requires storage and transportation methods that are both expensive and technologically complex, such as high-pressure systems (up to 700 bar) or cryogenic conditions (−252.8 °C) [9]. In addition, it is noteworthy that the current infrastructure for methane, commonly known as natural gas, is considerably more comprehensive and well-established in comparison to that of hydrogen. The aforementioned encompasses vast systems of pipelines, storage infrastructures, and diverse end-user implementations, spanning from power generation facilities and heating mechanisms to transportation means. The expenses and complexity involved in retrofitting the existing infrastructure to accommodate hydrogen utilization or constructing novel systems may pose a significant financial obstacle [10]. Methane exhibits certain chemical properties that give it favorable attributes relative to hydrogen. The reduced reactivity of the substance results in increased safety during handling and storage, thereby mitigating the potential hazards associated with possible leaks [11].

Several studies have determined that the power-to-methane pathway is technically feasible and capable of producing methane with high efficiency and scalability. Using a detailed distributed parameter method, one study analyzed a solar-powered power-to-methane system and found energy and exergy efficiencies of 9.88% and 11.08%, respectively, with a power-to-methane pathway yield of 914.51 MWh/y [12]. Wang et al. examine the design of a power-to-methane system based on co-electrolysis, focusing on the role of $CO_2$, pressurized stack operation, and internal methanation. Results indicate that pressurized operation and internal methanation can enhance system efficiency, with the highest efficiency achieved at a methane fraction of 15% vol.% at 15 bar and a potential efficiency of 90% on higher heating value[13]. Hervy et al. tested $CO_2$ methanation in a demonstration-scale fluidized bed reactor with an improved internal heat exchanger and found that the reactor displayed high efficiency and flexibility in the face of operating condition fluctuations associated with power-to-methane systems, with the temperature being the most influential operating condition in terms of conversion efficiency [14].

Several studies have assessed the techno-economic potential of the power-to-methane pathway in various contexts. Peters et al. presented a techno-economic analysis of power-to-methane as a sector coupling option for Germany's energy transition to renewable energy, with a process analysis revealing key insights and an economic analysis revealing methane costs in the range of $3.78 to $4.17 per kg, indicating no economic benefit for a gas provider [15]. Bellotti et al. assessed the technical and economic viability of four power-to-fuel solutions, including methane, methanol, ammonia, and hydrogen, with the Power-to-Hydrogen process being the most efficient, followed by methanol and ammonia, and methane being the least efficient. The study also reveals that the largest expenditures are related to the purchase of electrical energy and electrolyzer capital expenditure (CAPEX) and operational expenditure OPEX and that a 50% reduction in these costs could result in a significant reduction in fuel production costs [16]. Parra et al. evaluated the economic viability and environmental performance of power-to-gas (P2G) systems that produce hydrogen or synthetic natural gas (SNG). No system can compete economically with conventional gas production systems when selling only hydrogen and SNG; additional services are required to ensure economic viability. In addition, the contribution of "clean" renewable electricity to electrolysis is crucial for the environmental benefits of P2G relative to conventional gas production [17]. Salomone et al. investigated the coupling between a completely renewable energy-based electric profile and a P2G plant for SNG production. The levelized cost of SNG ranged between 64.5 $/MWh and 241.9 $/MWh, making it competitive with natural gas prices [18].

In the current research on power-to-methane pathways, the review of the literature identifies two gaps. The lack of studies examining the potential and economic viability of power-to-methane in specific regions or countries, as well as the effects of contextual factors such as regulatory frameworks and existing infrastructure, constitutes the first gap. The second gap is the need for additional research into the effect of input variables on the commercial viability of power-to-methane systems. The primary objective of this study is to assess the financial viability and profitability of a power-to-methane plant in Qatar over a 20-year period, utilizing key financial metrics such as net present value (NPV), internal rate of return (IRR), and levelized cost of methane (LCOM). LCOM is a metric utilized to assess the overall expenses associated with the production of methane throughout its lifespan. The calculation involves the division of the aggregate project cost by the overall quantity of methane generated. The LCOM metric holds significant utility in facilitating comparisons between diverse power-to-methane projects and in identifying the economic viability of a given project [19]. Calculating the LCOM of a power-to-methane project is crucial for a variety of reasons. First, it gives you a chance to weigh the costs of producing methane using fossil fuels versus renewable energy sources. Using this knowledge, decisions can be made regarding the most economical means of producing methane from an energy source [20]. The LCOM metric can be employed as a means of assessing the financial viability of a power-to-methane project. If the LCOM is below the prevailing market price of methane, it is probable that the project will yield profits. In the event that the LCOM surpasses the prevailing market value of methane, it is probable that the venture will not yield profits. The LCOM can also be used to pinpoint the major expenses that influence the cost of a project that converts power to methane. This information has the potential to enhance the efficacy and cost-effectiveness of the project [21].

The study also aims to conduct a sensitivity analysis examining the effects of varying key parameters, such as the selling price of methane, purchased $CO_2$, and discount rates, in order to determine the conditions under which the power-to-methane plant becomes financially viable and profitable. Ultimately, this study aims to provide valuable insights and recommendations for future decision-making processes and development strategies for power-to-methane technologies, contributing to the transition toward renewable energy systems.

## 2. Methodology

This study employs a techno-economic analysis technique, which is a technique used to evaluate the technical and financial feasibility of a project [22]. The following steps comprise the methodology for conducting a techno-economic analysis for the production of renewable methane:

i. Scope of the study

The specific objective of the study is the production of renewable methane in Qatar. The geographical and technical limits of the plant, including its location, feedstock sources, and methods for producing renewable gas, comprise the scope of the study. The plant is hypothetically located in Qatar's Ras Laffan Industrial City, 80 km northeast of Doha. The location was chosen due to its strategic proximity to industrial plants and its ready infrastructure and supporting facilities. Regarding feedstock sources and methods for producing renewable gas, solar energy is used to power the plant, seawater is used to produce hydrogen ($H_2$), $CO_2$ is purchased, and renewable methane is produced through a methanation process. Injecting renewable methane into the grid using an injection station. The study's limitations include resource limitations. Due to the scarcity of fresh water in Qatar, seawater desalination is required.

ii. Process design

A mass and energy balance method is utilized to calculate the mass and energy inputs and outputs of a production process. Solar power generation is the initial step in the renewable methane production process design. The 10 MW of electricity generated by solar panels is used to power the water electrolysis process. Reverse osmosis (RO) is used to produce the high-quality water required for the water electrolysis process from seawater. Around 1.93 $m^3$ of seawater is required per hour. Water is electrolyzed to produce $H_2$ and oxygen ($O_2$). The process produces 216 kg of $H_2$ and 1712 kg of oxygen per hour. After the water electrolysis process produces $H_2$, it is stored in a high-pressure storage tank before being sent to the catalytic methanation process to produce renewable methane. Before being combined with $CO_2$, the $H_2$ produced by the electrolysis of water is stored in a high-pressure tank. $CO_2$ is purchased from a plant in Qatar's Ras Laffan Industrial City, which will supply the production process with captured $CO_2$. The $H_2$ is combined with the purchased $CO_2$ using the Sabatier reaction to produce renewable methane. Based on the provided parameters, 1177 kg of $CO_2$ is required to produce 429 kg of methane, along with 1.48 MW of heat and 964 kg of water. The renewable methane produced in the Sabatier reaction is compressed to high pressure and stored in a suitable container. The final use of renewable methane is the injection into the natural gas grid. Fig. 1 shows a block flow diagram with the mass and energy balance of the renewable methane plant. Appendix A in the supplementary file includes a detailed breakdown of the mass and energy balance calculations, along with the equations used to perform the calculations.

iii. Cost estimation

In this study, we evaluate the revenue assumptions and operating expenses of a renewable methane plant to determine its economic feasibility. The revenue assumptions for the plant consist of three main components: $CH_4$, $O_2$, and heat. These outputs contribute to the plant's overall revenue because they can be sold on multiple markets, including the natural gas, industrial gases, and heating industries. In contrast, the operating expenses primarily consist of electricity, $CO_2$, and water consumption costs. Electricity is required to power the plant's operations and maintain optimal conditions, whereas $CO_2$ and $H_2O$ are production process inputs. To provide a comprehensive overview of the plant's economic performance, we have compiled a table with the revenue assumptions and operating expenses. Table 1 displays the quantities and costs of each component necessary for calculating the profitability of the plant and determining its financial viability. It should be noted that for the purpose of this analysis, all financial values are expressed in United States Dollars (USD), unless stated otherwise.

In addition, we intend to provide a comprehensive understanding of the capital costs associated with the building and operation of the renewable methane plant. Capital expenses are crucial in determining the plant's viability and overall profitability. The capital cost components for this plant include plant equipment, construction and building, office equipment, and furniture and fixtures. The plant equipment, with a cost of $33,445,606, constitutes the largest proportion of the capital expenditure. It includes all machinery, apparatus, and devices necessary for the plant's efficient operation, from the processing of raw materials to the manufacturing of the final product. The total cost of capital, including all of the aforementioned components, is $46,751,218. Table 2 presents the specific costs for plant equipment, construction and building, office equipment, and furniture and fixtures of power to the methane plant. Additionally, Appendix B in the supplemental file includes additional information regarding each capital cost component. It provides a detailed breakdown of the expenses within each category, providing additional insight into the various investments required for the establishment and operation of the renewable methane plant.

The primary components of the operating costs include the cost of manufacturing, repair and maintenance, salaries and related staff cost -

**Table 1**
Operating expenses and revenue assumptions of renewable methane plant.

| Product Name | Unit | Selling Price | Consumption Cost | Reference |
|---|---|---|---|---|
| Revenue assumption | | | | |
| $CH_4$ | $/kg | 2.00 | | [23] |
| $O_2$ | $/kg | 0.05 | | [24] |
| Heat | $/MW | 25 | | [25] |
| Operating expenses | | | | |
| Electricity | $/MW | | 15.67 | [26] |
| $CO_2$ | $/kg | | 0.60 | [27] |
| Water | $/kg | | 0.0003 | [26] |

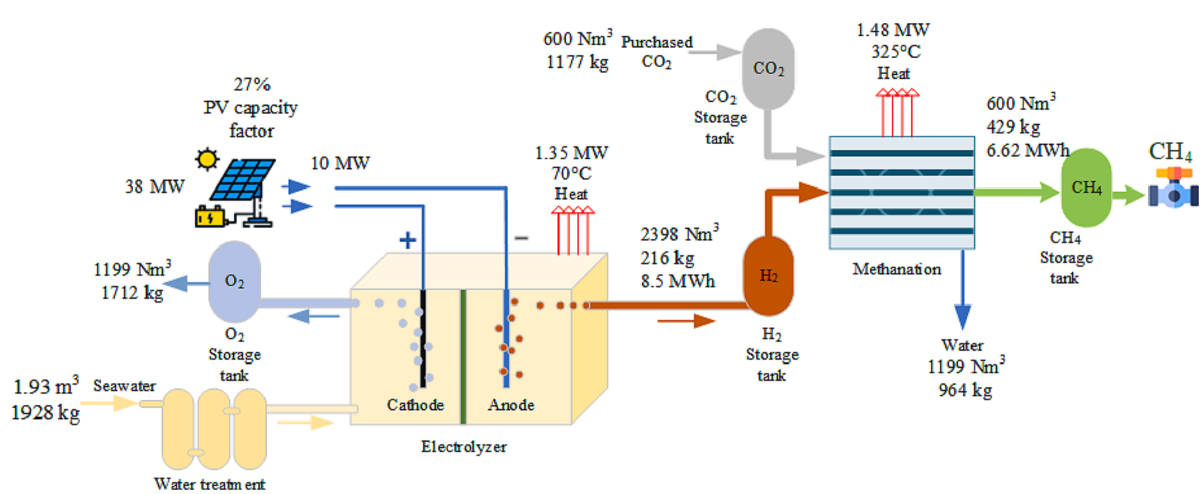


**Fig. 1.** Block flow diagram with mass and energy balance of the renewable methane plant.

**Table 2**
Detailed cost breakdown for the construction of a 10 $MW_{el}$/6.62 MW renewable methane production facility, including construction, building, plant equipment, office equipment, pre-operating expenses, working capital, and contingencies, with references to detailed cost components in Appendix B and Appendix C.

| Component | Cost ($) of 10 $MW_{el}$/6.62 MW $_{renewable\ methane}$ | Reference |
|---|---|---|
| **Construction and Building** | 11,796,164 | [28] More details are in Table 5 – Appendix C |
| **Plant equipment** | | |
| Renewable (Solar) | 25,726,000 | [29] |
| Seawater Desalination (RO system) | 37,056 | [30] |
| Electrolysis (PEM) | 5,000,000 | |
| $H_2$ storage tank | 332,500 | |
| $CO_2$ storage tank cost | 82,400 | |
| $CO_2$ compressor | 252,625 | More details are in Table 6 – Appendix C |
| $H_2$ compressor | 252,625 | |
| $O_2$ storage tank | 82,400 | |
| Methanation | 1,400,000 | |
| Gas grid injection station | 280,000 | |
| Total cost | 33,445,606 | |
| **Office equipment** | 4,258 | [31] More details are in Table 7 – Appendix B |
| **Computer and other related accessories** | 33,973 | [32] More details are in Table 7 – Appendix B |
| **Furniture and fixture** | 37,500 | [33] More details are in Table 7 – Appendix B |
| **Pre-operating expenses** | 336,081 | [30] More details are in Table 8 – Appendix C |
| **Working capital** | 192,801 | [34] More details are in Table 9 – Appendix D |
| **Provision for contingencies** | 904,835 | [35] More details are in Table 7 – Appendix B |
| **Total cost** | **46,751,218** | |

direct, utilities and plant overheads, lease rental, salaries, and related staff cost - indirect, communication expenses, marketing expenses, and courier and stationery. The cost of manufacturing, which amounts to $6,905,861, constitutes the largest portion of the operating costs. It covers the expenses related to electricity, $H_2O$, and $CO_2$, which are necessary inputs for the plant's production process. The total operating cost, incorporating all the listed components, comes to $8,515,624.7. Table 3 presents the specific costs for all categories, enabling stakeholders to evaluate the distribution of expenses across the various aspects of the plant's operation in the first year only. Furthermore, Appendix D in the supplemental file includes more detailed information on each operating cost component throughout the lifetime of the plant. It offers a thorough breakdown of the expenses within each category, giving stakeholders a deeper understanding of the costs required to maintain and run the renewable methane plant.

The capital costs and operating costs of a power-to-methane plant are used to calculate the profit and loss (P&L) statement, balance sheet, and cash flow statement. The P&L statement summarizes the revenues, costs, and expenses during a specific period [37], as shown in Eq. (1). The balance sheet provides a snapshot of the plant's assets, liabilities, and equity at a specific point in time [38]. The cash flow statement shows how cash moves in and out of the plant during a specific period, divided into three sections: operating activities, investing activities, and financing activities [39].

$$Net\ Income = Revenues - (Operating\ Costs + Depreciation + Interest\ Expense + Taxes) \quad (1)$$

**Table 3**
Breakdown of costs for a 10 $MW_{el}$/6.62 MW renewable methane production facility, including manufacturing, repair and maintenance, salaries, utilities, and administrative expenses, with references to detailed cost components in Appendix B and Appendix D.

| Component | Cost ($) of 10 $MW_{el}$/6.62 MW $_{renewable\ methane}$ | Reference |
|---|---|---|
| **Cost of manufacturing** | | |
| Cost of Electricity | 1,253,600 | [26] More details are in Table 1 – Appendix B |
| Cost of $CO_2$ | 5,649,600 | [27] More details are in Table 1 – Appendix B |
| Cost of Water | 2,661 | [26] More details are in Table 1 – Appendix B |
| Total cost | 6,905,861 | |
| **Repair and Maintenance** | | |
| Solar unit 2 %CAPEX/a | 514,520 | [30] |
| Desalination 4 %CAPEX/a | 1,482 | |
| Electrolysis 4 %CAPEX/a | 200,000 | |
| $H_2$ storage tank 2 % CAPEX/a | 4,987.5 | |
| $CO_2$ storage tank costs 4 %CAPEX/a | 2,884 | |
| $O_2$ storage tank 2 % CAPEX/a | 1,236 | |
| Gas grid injection station 2% CAPEX/a | 5,600.00 | |
| Methanation 10 % CAPEX/a | 140,000 | |
| Total cost | 870,709.7 | |
| **Salaries and related Staff cost - direct** | 72,947 | [34] More details are in Table 4 – Appendix B |
| **Utilities and plant overheads** | 24,000 | [26] More details are in Table 9 – Appendix D |
| **General and administrative expenses** | | |
| Lease rental | 197,260 | [34] More details are in Table 9 – Appendix D |
| Salaries and related staff cost - indirect | 72,947 | [34] More details are in Table 3 – Appendix B |
| Communication expenses | 6,575 | [36] More details are in Table 9 – Appendix D |
| Marketing expenses | 2,740 | [36] More details are in Table 9 – Appendix D |
| Courier and stationery | 6,575 | [33] More details are in Table 9 – Appendix D |
| **Total cost** | **8,515,624.7** | |

iv. Calculation of levelized costs

To calculate the levelized costs of a power-to-methane plant, one must first collect the relevant plant data and assumptions, including capital costs, operational expenses, financing information, and plant efficiency metrics. Next, calculating total lifetime cost by factoring in both CAPEX and OPEX, as well as discount rates (10%) and project lifespan (20 years), as shown in Eq. (2).

$$Total\ Lifetime\ Cost = \sum_{n} \frac{Total\ CAPEX\ and\ OPEX_n}{(1 + discount\ rate)^n} \quad n = time\ period \quad (2)$$

Similarly, calculating the total lifetime output of expected production for each year, taking into account the plant's capacity, efficiency, and any potential changes in output over its operational life, as shown in Eq. (3).

$$Total\ Lifetime\ Output = \sum_{n} \frac{Methane\ Production_n}{(1 + discount\ rate)^n}\quad n = time\ period \tag{3}$$

Finally, to determine the levelized cost, we divide the total lifetime cost by the total lifetime output, as shown in Eq. (4).

$$Levelized\ Cost\ of\ Methane = \sum_{n} \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Output} \tag{4}$$

v. Sensitivity analysis

For a sensitivity analysis of the power-to-methane plant using the provided values, the following parameters will be adjusted to assess their impact on the levelized cost:

(i) **Selling price of methane**. By varying the selling price of methane, we can determine how changes in the revenue generated from methane sales will impact the plant's overall economics. Consider various scenarios in which the selling price increases or decreases from the base value of $2 per kg.
(ii) **$CO_2$ costs.** In Qatar, the production of natural gas is a significant economic driver, and the country is the world's largest exporter of liquefied natural gas [40]. As a result, the use of power-to-methane technology to produce renewable natural gas has the potential to be a critical component of the country's energy mix. To optimize the techno-economic performance of power-to-methane plants in Qatar, it is essential to consider the cost of $CO_2$ sources. $CO_2$ is a crucial input for power-to-methane plants, so changes in the cost of $CO_2$ can affect the overall plant economics. We will conduct a sensitivity analysis by varying the source of purchasing $CO_2$ cost to determine how the levelized cost is affected.
(iii) **Discount rate**. The discount rate reflects the time value of money and is used to calculate the net present value of future costs and revenues. In this instance, a base discount rate of 10% is provided. We will analyze the impact of various discount rates on the levelized cost to determine how changes in the perceived risk or opportunity cost of capital affect the viability of the plant. Table 4 summarizes the base and variance values used in this study.

## 3. Results and discussion

In this section, the results of the considered power-to-methane plant techno-economic analysis will be presented. The plant's economic viability is assessed by analyzing key financial metrics, including capital and operational expenditures, profit and loss statements, balance sheets, cash flows, and the levelized cost of methane (LCOM) production. In addition, an insight into the plant's financial attractiveness and profitability is presented by calculating its NPV and IRR. In addition, a sensitivity analysis is performed to determine the effect of changing key input parameters, such as the selling price of methane, $CO_2$ costs, and discount rate, on the LCOM, NPV, and IRR. This analysis identifies the most important economic drivers of the plant and assesses its adaptability to varying market conditions.

**Table 4**
Base and variance values used in the sensitivity analysis.

| | Unit | Base | Variance | Reference |
|---|---|---|---|---|
| Selling price of methane | $/kg | 2 | 1.5 – 3.5 | [41] |
| $CO_2$ costs | $/kg | 0.60 | 0.03 ($CO_2$ from natural gas processing)<br>0.12 ($CO_2$ from cement)<br>0.60 ($CO_2$ from direct air capture) | [42] |
| Discount Rate | % | 10 | 0 – 20 | |

### 3.1. CAPEX

The CAPEX for the power-to-methane plant can be categorized into three main segments: plant and machinery, construction and building, and others. Plant and machinery represent the largest portion of the investment, consuming $33,445,606, or 72% of the total cost. The high cost in this category is primarily driven by the expense of solar energy systems, which accounts for $25,726,000, or 55% of the plant and machinery costs. This significant expense can be attributed to the need for a reliable, sustainable, and efficient energy source to power the plant's operations, given that electricity is a key input for the power-to-methane process. Construction and building are the second-largest categories, comprising $11,796,164 or 25% of the total investment costs. These expenses correspond to the construction of the physical infrastructure required to house and support the plant's operations, including the buildings, facilities, and other structures. The remaining costs, categorized as others, amount to $1,509,448 or 3% of the total investment costs. This category includes expenses related to furniture and fixtures, office equipment, computer, and related accessories, pre-operating expenses, working capital, and provisions for contingencies. While these costs are smaller in comparison to the other categories, they are essential for the successful establishment and operation of the power-to-methane plant. In summary, Fig. 2 presents a breakdown of initial investment costs for the power-to-methane plant, highlighting the dominance of plant and machinery costs driven by the solar energy system.

### 3.2. OPEX

The OPEX associated with the power-to-methane plant can be divided into three main categories: cost of manufacturing, repair, maintenance, and others. The cost of manufacturing category represents the largest share of OPEX, amounting to $6,905,861 or 85% of the total operational expenses. Within this category, the cost of electricity and the cost of $CO_2$ are the most significant contributors. The cost of electricity accounts for 15% of the manufacturing costs, as electricity is an essential

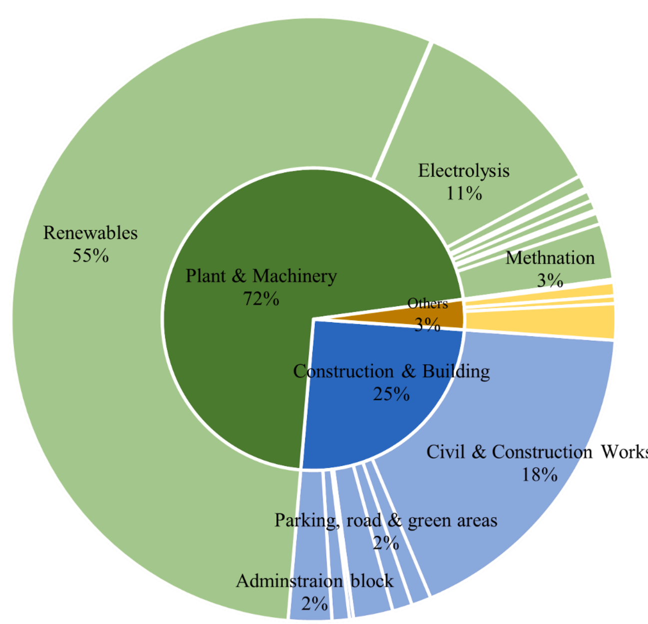


**Fig. 2.** Breakdown of initial investment costs for the power-to-methane plant. A detailed breakdown of initial investment costs can be found in Table 13 -Appendix G.

input for the power-to-methane production process. Although the plant utilizes solar power as a sustainable and economical source of electricity, it poses particular challenges. For plants to run continuously, robust energy storage solutions are required due to the fluctuating availability of solar power caused by weather changes [43]. The need for action to tackle this challenge necessitates investment in energy storage systems that are both adequate and effective. The cost of purchased $CO_2$, which is a crucial raw material for methane production, constitutes 69% of the total cost of manufacturing. The purchase of $CO_2$, which constitutes a substantial proportion of production expenses, poses difficulties with regard to the dependability of supply, instability of market prices, and the possibility of future carbon pricing [44]. In order to achieve cost-effectiveness and sustainability, it may be advantageous to implement strategies such as procuring extended supply contracts and investigating carbon capture technologies. The repair and maintenance category includes the expenses related to maintaining and repairing the plant's equipment and facilities, amounting to $870,710 or 11% of the total OPEX. Regular repair and maintenance activities are essential to ensure the plant operates efficiently and to prevent unexpected breakdowns or production disruptions. Moreover, retaining qualified staff, maintaining a spare parts inventory, and performing routine preventive maintenance are all essential components of effective repair and maintenance cost management. The implementation of these measures is of utmost importance in order to prevent unforeseen operational interruptions and to uphold optimal plant productivity. The remaining operational expenses, totaling $383,044 or 5% of the OPEX, cover a variety of costs, including (i) wages and benefits for employees directly involved in the production process, (ii) costs for services like water, heating, and waste management, as well as other plant-related expenses, (iii) expenses associated with leasing land or facilities for the plant. (iv) wages and benefits for employees not directly involved in the production process, such as administrative and support staff, (v) costs related to telephone, internet, and other communication services required for the plant's operations, (vi) expenses incurred in promoting and selling the plant's methane output, such as advertising and public relations efforts, and (vii) costs associated with shipping, mailing, and purchasing office supplies. Challenges arise in relation to staff retention, efficient utility use, and effective plant management with respect to various operational expenses. The implementation of comprehensive human resource policies, energy conservation practices, and efficient plant management strategies is crucial for cost control purposes. Robust financial planning and risk management strategies are deemed essential due to the potential variability in the costs of raw materials, utilities, and labor. Comprehending market trends, proficiently managing the supply chain, and implementing proactive maintenance planning are crucial aspects of mitigating risks linked to cost fluctuations. In summary, Fig. 2 presents a breakdown of OPEX for the power-to-methane plant, with the cost of $CO_2$ and electricity being the most significant contributors. Additionally, repair and maintenance expenses, as well as various other costs associated with staffing, utilities, and plant operations, contribute to the overall operational expenditures (See Fig. 3).

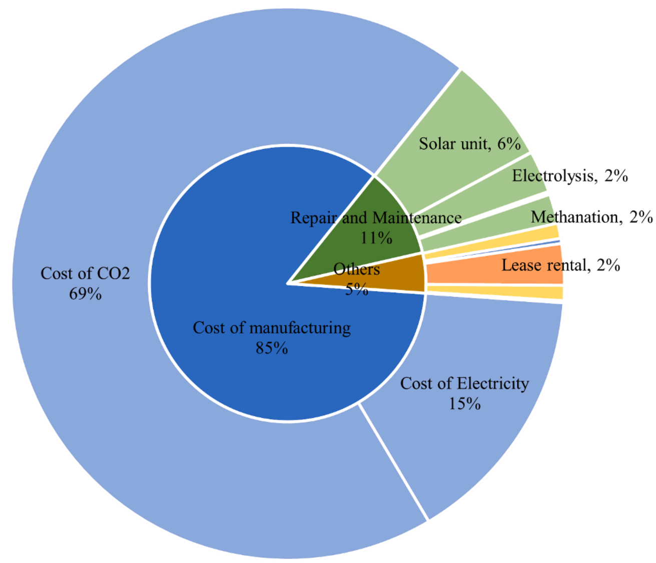


**Fig. 3.** Breakdown of OPEX for the power-to-methane plant. A detailed breakdown of OPEX can be found in Table 14 - Appendix G.

### 3.3. Profit and loss (P&L) statement

The P&L statement shows the financial performance of a power-to-methane plant over a period of five years, as shown in Table 5, and the full table for 20 years is provided in Table 9 - Appendix D. The P&L statement shows a consistent rise in the plant's expenses over time, including operating costs and general and administrative costs. There are a number of connected factors that have caused this escalation. First, the cost of manufacturing has risen primarily as a result of an overtime gradual increase in the price of raw materials, particularly $CO_2$. Given how important $CO_2$ is to manufacturing costs, even small changes in its market price have a big impact on overall manufacturing costs. Second, the increase in Salaries & Related Staff Costs is the result of the plant's increased operational requirements due to the expansion of its production capacity. Additionally, rising staff costs are a result of market trends in wages and inflation. Thirdly, utilities and plant overheads have increased as well, reflecting gradually rising utility rates. Additionally, the cost of utilities and overheads rises as the plant's operations grow, which also adds to the cost increase. Fourthly, general and administrative expenses, including rent payments on leases, indirect staff costs, communication costs, marketing costs, and others, are subject to operational scaling and inflation. The aforementioned variables have contributed to a gradual escalation of the associated expenses. The recurring nature of the plant's maintenance schedule has kept repair and maintenance costs constant in the meantime. Finally, the significant depreciation costs observed can be attributed to the substantial initial investment made in the plant, property, and equipment. The straight-line depreciation method that has been selected distributes the cost uniformly throughout the assets' lifespan, leading to elevated depreciation expenses during the initial years.

The plant's revenue has been steadily increasing over the years, reaching a total of $18,738,299 in year 20. However, the plant's expenses, including operating expenses and general and administrative expenses, have also been increasing over the years. The gross profit, which is the difference between revenue and the cost of products sold (methane, heat, and $O_2$), has been increasing over the years, indicating that the plant is becoming more profitable. Similarly, the net operating income has also been increasing each year, showing that the plant is generating more income after accounting for all operating expenses. However, looking at the net profit, which is the bottom line, it is noticeable that the plant has incurred losses in the first three years. The losses are mainly due to high depreciation expenses, which are non-cash expenses, and the high cost of manufacturing in year 1. Nonetheless, the plant has been profitable from year eight onwards, with a net profit of $386,811 in year eight and a total net profit of $7,597,298 in year 20.

### 3.4. Balance sheet

Based on the provided balance sheet, which can be found in Table 11 – Appendix E, it can be seen that the non-current assets of the power-to-methane plant are primarily composed of property, plant, and equipment with a gross book value of $45,317,501. Over the course of 20 years, the accumulated depreciation on these assets amounts to $40,804,916, resulting in a net book value of $4,512,584. The current assets of the plant consist of accounts receivable, prepayments and other receivables, and cash and bank balances, with a total value of

**Table 5**
Profit and Loss statement for a Power-to-Methane plant over five years with the full table for 20 years provided in Table 9 - Appendix D.

| Description | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| **Revenue** | 8,114,800 | 8,464,848 | 8,832,124 | 9,217,488 | 9,621,841 |
| **Operating expenses** | | | | | |
| Salaries & related Staff cost - Direct | 72,947 | 76,589 | 80,413 | 84,428 | 88,644 |
| Cost of Manufacturing | 6,905,861 | 6,930,986 | 6,956,614 | 6,982,754 | 7,009,417 |
| Utilities and plant overheads | 24,000 | 25,200 | 26,460 | 27,783 | 29,172 |
| **Total operating expenses** | 7,002,807 | 7,032,774 | 7,063,486 | 7,094,965 | 7,127,233 |
| Gross Profit/(Loss) | 1,111,993 | 1,432,074 | 1,768,638 | 2,122,524 | 2,494,608 |
| **General and administrative expenses** | | | | | |
| Lease rental | 197,260 | 197,260 | 197,260 | 197,260 | 197,260 |
| Salaries & related Staff cost - Indirect | 72,947 | 76,589 | 80,413 | 84,428 | 88,644 |
| Communication Expenses | 6,575 | 7,890 | 9,468 | 11,362 | 13,635 |
| Marketing Expenses | 2,740 | 2,740 | 2,740 | 2,740 | 2,740 |
| Courier & Stationery | 6,575 | 6,773 | 6,976 | 7,185 | 7,401 |
| Repair & Maintenance | 870,710 | 870,710 | 870,710 | 870,710 | 870,710 |
| Pre-operating expenses | (69,615) | – | – | – | – |
| **Total general expenses** | 1,087,192 | 1,161,961 | 1,167,567 | 1,173,685 | 1,180,389 |
| Net Operating income | 24,800 | 270,112 | 601,072 | 948,839 | 1,314,219 |
| Depreciation | 2,164,015 | 2,164,015 | 2,164,015 | 2,164,015 | 2,164,015 |
| **Net profit** | (2,139,215) | (1,893,903) | (1,562,944) | (1,215,177) | (849,796) |

$82,114,138 at the end of the 20th year. This shows a significant increase from the initial amount of $933,679 at year 0, which can be attributed to the successful implementation and operation of the power-to-methane plant.

On the equity and liabilities side, the capital/equity remains constant at $46,751,218 throughout the 20 years, while the retained earnings start from a negative value of $270,098 at year 0, gradually increasing to $31,467,376 at year 19. This signifies a positive trend in the plant's profitability over time. The non-current liabilities of the plant are relatively insignificant, with staff termination benefits amounting to only $156,526 at the end of year 20. Meanwhile, the current liabilities consist of accounts payable and accrued expenses with a total value of $654,305 in year 20. Overall, the balance sheet reveals a positive financial status of the power-to-methane plant, with a steady increase in equity and profitability over the years. It also demonstrates efficient management of assets and liabilities, resulting in a significant increase in the plant's cash and bank balances. However, more detailed analysis and comparison with industry standards and benchmarks may be necessary to assess the plant's financial performance in a broader context.

### *3.5. NPV, IRR, and LCOM*

Table 6 provides information on the net cash flow, total cash inflow, total cash outflow, NPV, IRR, and LCOM of a power-to-methane plant over a period of five years, and the full table for 20 years is provided in Table 12 – Appendix F.

The key findings provide valuable insights into the viability and profitability of the power-to-methane plant. In a sensitivity analysis, which will elucidate the conditions necessary for the power-to-methane plant to become financially viable and profitable, these insights will be investigated further. The performed analysis revealed the following key insights:

- The net cash flow from operations increased over the lifetime of the power-to-methane plant, indicating a growing capacity to generate cash. However, it was not enough to cover the initial investment and ongoing costs.
- The power-to-methane plant experienced sporadic cash outflows over the course of the period, reflecting the costs and expenses associated with its development, operation, and maintenance.
- NPV of the power-to-methane plant, calculated using a discount rate of 10%, was found to be negative −3,818,163. This implies that the power-to-methane plant is expected to generate a net loss over the 20-year period, rendering it financially unviable based on the current assumptions.
- IRR for the power-to-methane plant was −1%, further emphasizing the plant's lack of profitability under the given conditions.
- LCOM was calculated to be 1.75 $/kg, providing a useful benchmark for comparing the cost of methane production with alternative plants or energy sources.

To gain a deeper understanding of the potential viability of the

**Table 6**
Summary of financial performance indicators for a power-to-methane plant over a five-year period, including net cash flow, total cash inflow, total cash outflow, NPV, IRR, and LCOM. The complete 20-year analysis can be found in Table 12 – Appendix F.

| Description | Year 0 | Year 1 | Year 2 | Year 3 | Year 4 |
|---|---|---|---|---|---|
| Present value factor | 10.0% | 0.909090909 | 0.826446281 | 0.751314801 | 0.683013455 |
| Net Cashflow from Operations | | (76,367) | 247,933 | 577,744 | 924,304 |
| Total Cash Inflow | | (76,367) | 247,933 | 577,744 | 924,304 |
| Total Cash Outflow | (45,317,501) | – | – | – | (33,973) |
| Net Cash flow | (45,317,501) | (76,367) | 247,933 | 577,744 | 890,331 |
| PV of Net Cashflow | (45,317,501) | (69,424) | 204,904 | 434,068 | 608,108 |
| NPV | (3,818,163) | | | | |
| IRR | −1% | | | | |
| LCOM ($/kg) | 1.75 | | | | |

power-to-methane plant, a sensitivity analysis will be conducted. This analysis will examine the effects of varying key parameters, such as the selling price of methane, electricity costs, and purchased $CO_2$ discount rates, to determine the financial viability and profitability of the plant. By identifying these conditions, future power-to-methane plant development and decision-making processes can be better informed. As currently modeled, the power-to-methane plant is neither financially viable nor profitable. However, the upcoming sensitivity analysis will shed light on the conditions that could lead to a positive NPV and an acceptable IRR, thereby making the plant an investment worth making.

### 3.6. Sensitivity analysis

Fig. 4 presents a sensitivity analysis of the power-to-methane plant, focusing on the impact of the annual operational hour of the plant on LCOM. The reference point for this analysis is the annual operational hour of 8000 h. The sensitivity analysis examines how the plant's LCOM is affected by different annual operational hours, ranging from 2000 h to 8760 h. This assessment is essential for understanding the financial viability of the plant under various market conditions and pricing scenarios.

The sensitivity analysis reveals several trends concerning the relationship between the annual operating hours and the LCOM. At the lower end of the scale, with 2,000 annual operational hours, the LCOM is found to be $2.90. As the annual operational hours doubled to 4,000, the LCOM decreased significantly to $2.14. This trend of decreasing LCOM continues as the annual operational hours increase further. At 6,000 operational hours, the LCOM drops to $1.88, and at 8,000 operational hours, it reaches $1.75. When the plant operates at its maximum capacity, with 8,760 operational hours per year, the LCOM is at its lowest value of $1.72. The observed decrease in LCOM with increasing annual operational hours can be attributed to the increased utilization of the plant infrastructure, which results in a more efficient distribution of the fixed costs associated with the plant's construction and maintenance. Additionally, the increased production volume of renewable methane permits economies of scale, which can reduce production costs. Additionally, Table 7 compares LCOM values from our study with values found in the literature, highlighting the general alignment and variations between the studies to provide a comprehensive overview of methane production costs across different contexts and technologies. Our study's LOCE values, ranging from $1.75 to $2.90/kg with a base value of $1.75/kg, generally align with the values found in the literature. In some instances, the LCOM values from the literature exhibit a substantial overlap with our findings, whereas, in others, there are discernible differences. Variations in the underlying assumptions and methodologies may account for these discrepancies, as well as differences in capital costs, feedstock prices, technology efficiency, regional factors, and the scope of each study. For example, we found that the LCOM ranges from 1.75 to 2.90 \$/kg. This is lower than the LCOM range found in the literature, which is 4–4.9 \$/kg. One of the main reasons for this difference is the high cost of electricity in the literature [45]. The cost of electricity is a critical component of the overall cost of the power-to-methane plant. In the literature, the high cost of electricity has a significant impact on the LCOM. In contrast, our sensitivity analysis takes into account the cost of electricity in Qatar, where it is relatively cheap. This lower cost of electricity in Qatar has a significant impact on the overall LCOM of the power-to-methane plant. The lower LCOM in Qatar due to the low cost of electricity is a significant advantage for the country. This advantage makes the power-to-methane technology more financially viable in Qatar compared to other countries with higher electricity prices. This advantage can also be leveraged to make Qatar a leader in the production of renewable methane.

**Table 7**
Comparison of LCOM values from our study with values found in the literature.

| LCOM from our study | Unit | LCOM from the literature | Unit | Reference |
|---|---|---|---|---|
| 1.75–2.90 | \$/kg | 4–4.9 | \$/kg | [45] |
| | | 0.56–3.4 | | [46] |
| | | 1.16–2.07 | | [47] |
| | | 2.01 | | [48] |
| | | 1.66–2.45 | | [49] |

Table 8 presents a sensitivity analysis of the power-to-methane plant, focusing on the impact of varying $CO_2$ costs from different sources on the NPV and the LCOM. After conducting a sensitivity analysis of the power-to-methane plant, we revealed that sourcing $CO_2$ from natural gas processing plants in Qatar is the most viable option. By sourcing $CO_2$ from

**Table 8**
Sensitivity analysis of the power-to-methane plant, demonstrating the impact of varying $CO_2$ costs from different sources on NPV and LCOM, highlighting the influence of $CO_2$ sourcing scenarios on the plant's financial performance.

| $CO_2$ source | $CO_2$ cost (\$/kg) | NPV (\$) | LCOM (\$/kg) |
|---|---|---|---|
| Natural gas processing | 0.03 | 21,332,702 | 0.88 |
| Cement | 0.12 | 14,182,167 | 1.13 |
| Direct Air Capture | 0.60 | (3,818,163) | 1.75 |

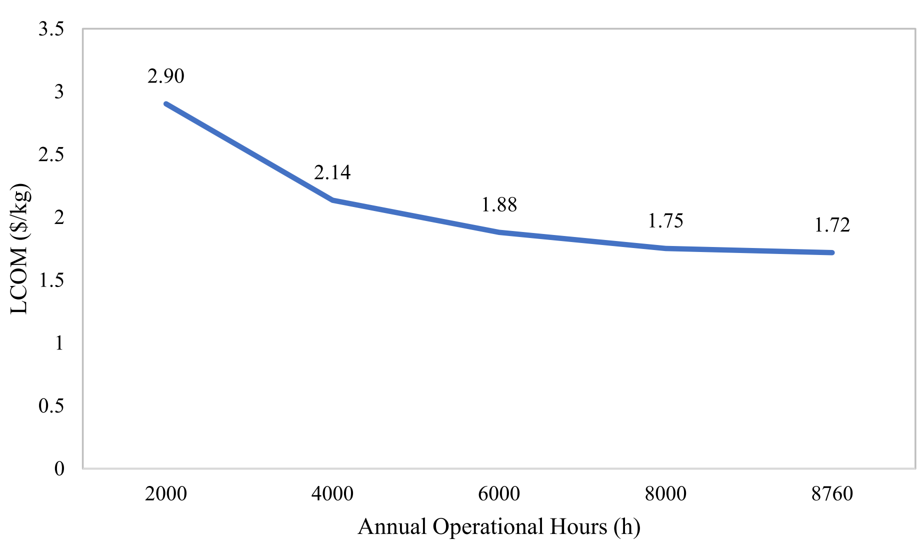


**Fig. 4.** Sensitivity analysis of the power-to-methane plant, illustrating the relationship between annual operational hours and the LCOM, highlighting the influence of varying annual operational hours on the plant's financial performance.

natural gas processing plants, the cost of $CO_2$ is significantly reduced, resulting in a more financially viable plant. At a $CO_2$ cost of $0.03/kg, the NPV is significantly positive, at $21,332,702, and the LCOM is $0.88/kg. This scenario indicates that the plant is financially viable and profitable, as the lower $CO_2$ cost improves the plant's overall economics. When $CO_2$ is sourced from direct air capture at the cost of $0.60/kg, the financial performance of the plant declines. The NPV falls to -$3,818,163, and the LCOM rises to $1.75/kg. The negative NPV indicates a net loss over the lifetime of the plant, and the higher $CO_2$ cost has a negative impact on the economics of the plant. Sourcing $CO_2$ from cement production at the cost of $0.12/kg is also an option, but the financial performance of the plant is reduced. The NPV decreases to $14,182,167, and the LCOM reduces to $1.13/kg. Although the financial performance has diminished, the plant remains profitable in this situation, as the NPV remains positive, and the LCOM is still relatively low. Based on our analysis, it is evident that the most viable option for optimizing the techno-economic performance of power-to-methane plants is to obtain $CO_2$ from natural gas processing plants in Qatar.

The advantages of sourcing $CO_2$ from natural gas processing plants in Qatar go beyond the power-to-methane plant's financial performance. The carbon footprint of Qatar's natural gas industry can be reduced by utilizing $CO_2$ from natural gas processing plants. This reduction in carbon footprint has the potential to be a significant step toward the country's carbon emission reduction goals. In addition to financial and environmental advantages, sourcing $CO_2$ from natural gas processing plants in Qatar may have geopolitical implications. Qatar can reduce its reliance on imported $CO_2$ by using $CO_2$ from domestic sources, which can be geopolitically advantageous given the region's current political climate.

Fig. 5 presents a sensitivity analysis of the power-to-methane plant, focusing on the impact of the selling price of methane on the NPV and the IRR. The sensitivity analysis examines how the plant's financial performance, as measured by NPV and IRR, is affected by different selling prices for methane, ranging from $1.5/kg to $3.5/kg. This assessment is essential for understanding the financial viability of the plant under various market conditions and pricing scenarios. As the selling price of methane increases, both NPV and IRR improve. This relationship indicates that higher selling prices lead to better financial performance for the plant. At a selling price of $1.5/kg, the NPV is significantly negative ($24,396,212.20), and the IRR is −5%. In this scenario, the plant is not financially viable, as it is expected to generate substantial losses. At the reference selling price of $2/kg, the NPV further improves to ($3,818,163.00), and the IRR rises to −1%. In this case, the plant is still not profitable, but the financial performance is closer to a break-even scenario. As the selling price continues to rise, both NPV and IRR improve. For instance, at a selling price of $2.5/kg, the NPV turns positive at $16,759,886.19, and the IRR increases to 3%. At higher selling prices of $3/kg and $3.5/kg, the NPV reaches $37,337,935.38 and $57,915,984.58, respectively, while the IRR grows to 7% and 10%. In these scenarios, the plant becomes financially viable and profitable. To sum up, the financial viability and profitability of the power-to-methane plant are highly sensitive to the selling price of methane. The plant becomes financially viable and profitable at selling prices above $2.5/kg, with the NPV turning positive and the IRR surpassing the break-even threshold.

The results of our sensitivity analysis demonstrate that an increase in the selling price of methane leads to an enhancement in both NPV and IRR. However, it is crucial to take into account the wider market dynamics and potential hazards associated with depending on these elevated prices to ensure the economic feasibility and profitability of the power-to-methane plant. Initially, the competitive environment may present a noteworthy obstacle. Supply might outpace demand as more competitors enter the market, potentially resulting in a drop in selling prices. In addition, the progression of technology may result in enhanced production techniques, thereby reducing expenses and ultimately causing a decline in prices. Furthermore, the dependence on elevated selling prices may render the facility vulnerable to fluctuations in the market. Like the price of any commodity, methane can change due to shifts in supply and demand dynamics, legislative changes, geopolitical factors, and other macroeconomic factors. The instability of revenues resulting from volatility has the potential to affect the financial performance of the plant. Moreover, the selling prices may be affected by regulatory risks. For instance, modifications to environmental regulations could affect the demand for methane and, as a result, its selling price. To summarize, the outcomes of our sensitivity analysis indicate that the financial performance of the power-to-methane plant can be enhanced by increasing the selling prices of methane. However, it is crucial to apply prudence while interpreting these results, considering the possible market dynamics and associated risks linked to the elevated prices. Hence, although elevated selling prices may enhance the plant's

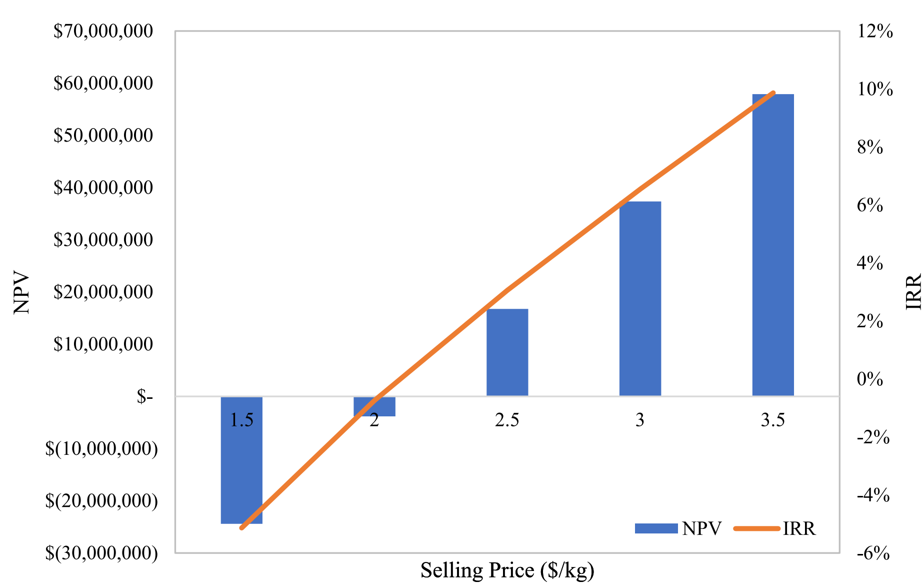


**Fig. 5.** Sensitivity analysis of the power-to-methane plant, illustrating the relationship between the selling price of methane and NPV as well as IRR, highlighting the influence of varying selling prices on the plant's financial performance and profitability.

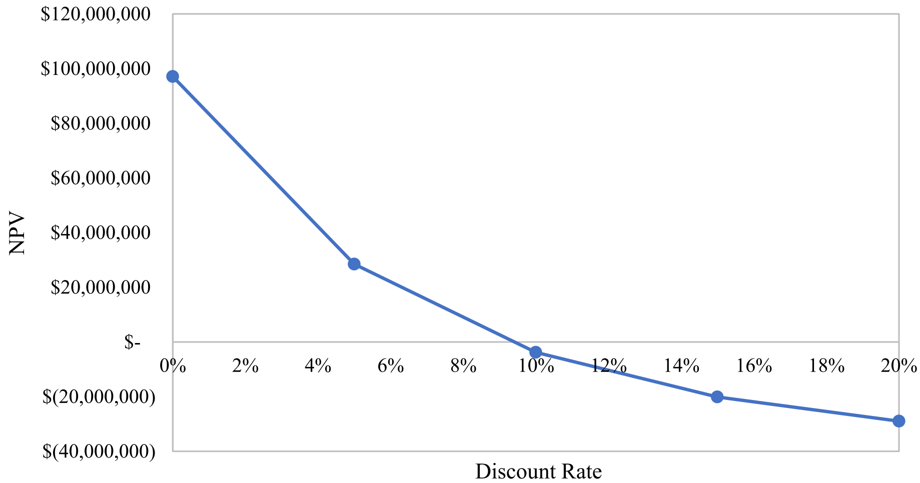


**Fig. 6.** Sensitivity analysis of the power-to-methane plant, showcasing the relationship between varying discount rates and NPV, highlighting the influence of different discount rates on the plant's financial evaluation and viability.

financial feasibility in the near future, a comprehensive risk management plan and expansion of income sources could guarantee the plant's enduring profitability and viability.

Fig. 6 presents a sensitivity analysis of the power-to-methane plant, focusing on the impact of varying discount rates on the NPV. This assessment is essential for understanding the financial viability of the plant under various assumptions of the time value of money and potential risks. As the discount rate increases, the NPV decreases. This relationship indicates that higher discount rates, which account for higher risk and opportunity costs, lead to a lower perceived value of the plant. At a discount rate of 0%, the NPV is significantly positive, at $97,133,187. In this scenario, the plant is considered highly financially viable, as future cash flows are valued equally to those generated today. When the discount rate increases to 5%, the NPV decreases to $28,446,706. At the reference discount rate of 10%, the NPV further declines to ($3,818,163). In this case, the plant is not financially viable, as the negative NPV indicates a net loss over the plant's lifetime. As the discount rate continues to rise, the NPV deteriorates further. For instance, at discount rates of 15%, the NPV falls to ($20,138,053). In this scenario, the plant is increasingly less financially viable, as the higher discount rates reflect greater risks and opportunity costs. In conclusion, the financial viability of the power-to-methane plant is highly sensitive to the chosen discount rate. The plant becomes less financially viable as the discount rate increases, with the NPV turning negative at a discount rate of 10%.

## 4. Conclusion

In conclusion, this study has provided a comprehensive techno-economic analysis of a power-to-methane plant in Qatar, using a rigorous methodology to evaluate both the technical feasibility and financial viability of such a plant. The results have enabled a better understanding of the economic potential of renewable methane production by providing insights into the investment and operational costs associated with similar plants.

Our primary findings indicate that the CAPEX for power-to-methane plants is dominated by plant and machinery costs, with the solar energy system constituting a substantial portion of the total investment (55%). The OPEX is driven primarily by the cost of inputs, with the cost of purchased $CO_2$ and electricity having the greatest impact. The detailed analysis of the plant's financial performance over the previous 20 years, including the profit and loss statement, balance sheet, and key insights into cash flow, NPV, IRR, and LCOM, reveals a mixed outlook. Despite increasing trends in gross profit and net operating income, the NPV and IRR suggest that the power-to-methane plant may not be financially viable under the current assumptions (selling price of methane is 2 $/kg and the cost of $CO_2$ is 0.6 $/kg), potentially resulting in a net loss over the 20-year period. This highlights important considerations about the feasibility of the plant and its ability to generate sustainable returns on investment. Various strategies could potentially address these financial challenges, including operational efficiencies, technological advancements, diversification of revenue streams, or changes in the financial structure of the plant.

The sensitivity analysis has shed light on the viability of the power-to-methane plant under various conditions. The financial performance of the plant is highly sensitive to key parameters such as the selling price of methane, the cost of electricity, and the cost of purchased $CO_2$. It is clear that the financial viability and profitability of these plants are subject to certain conditions and parameters, and changes in these can lead to a positive NPV and an acceptable IRR – (For example, if the selling price of methane is 2.5 $/kg and the cost of $CO_2$ is 0.6 $/kg). This knowledge can inform the decision-making processes and strategies for future power-to-methane plant development and investment, thereby contributing to the larger transition toward renewable energy and sustainable solutions. By identifying the critical factors that affect the profitability of power-to-renewable methane plants, stakeholders can optimize plant design, operations, and financial structures to create plants that are economically viable. These facilities can contribute to meeting global energy demands while reducing greenhouse gas emissions and accelerating the transition to a cleaner, more sustainable energy future.

In addition, future research can build upon the findings of this study to improve our understanding of the operations of power-to-renewable methane plants and their financial viability. The following areas of investigation are recommended for future research:

- Analyze the potential synergies and benefits of integrating power-to-methane plants with other renewable energy sources like wind and hydropower. Through such integration, investigating into the potential for energy storage, grid balancing, and demand management can reveal new opportunities for cost optimization and improved plant performance.
- Examine the impact of location-specific factors on the financial performance of power-to-methane plants, including resource availability, infrastructure, and market dynamics. Assessing the opportunities and challenges associated with developing these plants in various geographical contexts can aid stakeholders in identifying optimal plant deployment locations and strategies.

- Conduct a thorough life cycle assessment of power-to-methane plants in order to better comprehend their environmental impacts and viability. This evaluation should encompass the entire plant life cycle, from extraction and production of raw materials to operation, maintenance, and eventual decommissioning. Evaluating the environmental footprint, greenhouse gas emissions, and resource consumption of power-to-methane plants will provide a more comprehensive understanding of their sustainability credentials and assist in identifying areas for improvement.

Researchers and industry stakeholders can contribute to the ongoing development and deployment of power-to-renewable methane plants as a sustainable and economically viable solution for decarbonizing the energy sector by pursuing the recommended future studies.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Acknowledgments

The authors acknowledge the support provided by the Hamad Bin Khalifa University, Qatar Foundation, Qatar (210009034). Open Access funding is provided by Qatar National Library. The authors would also like to express their gratitude to Adnan Fareed, Senior Financial Analyst, for his valuable assistance in developing the economic model for this study.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cej.2023.144725.

## References

[1] I. Dincer, Renewable energy and sustainable development: A crucial review, Renew. Sustain. Energy Rev. 4 (2000) 157–175, https://doi.org/10.1016/S1364-0321(99)00011-8.
[2] A.A. Alola, I.O. Olanipekun, M.I. Shah, Examining the drivers of alternative energy in leading energy sustainable economies: The trilemma of energy efficiency, energy intensity and renewables expenses, Renew. Energy 202 (2023) 1190–1197, https://doi.org/10.1016/j.renene.2022.11.045.
[3] S. Ding, B. Guo, S. Hu, J. Gu, F. Yang, Y. Li, J. Dang, B. Liu, J. Ma, Analysis of the effect of characteristic parameters and operating conditions on exergy efficiency of alkaline water electrolyzer, SSRN Electron J. (2022), https://doi.org/10.2139/ssrn.4065639.
[4] Mihaescu L, Lazaroiu G, Grigoriu RM, Stanescu L, Dragne M, Negreanu GP, et al. An analysis of the efficiency of flue gases energy potential conversion through methanation, in: 2022 8th Int Conf Energy Effic Agric Eng EE AE 2022 - Proc 2022. https://doi.org/10.1109/EEAE53789.2022.9831228.
[5] M. Qi, J. Park, R.S. Landon, J. Kim, Y.i. Liu, I.l. Moon, Continuous and flexible Renewable-Power-to-Methane via liquid CO2 energy storage: Revisiting the techno-economic potential, Renew. Sustain. Energy Rev. 153 (2022) 111732, https://doi.org/10.1016/j.rser.2021.111732.
[6] A. Aghahosseini, A.A. Solomon, C. Breyer, T. Pregger, S. Simon, P. Strachan, A. Jäger-Waldau, Energy system transition pathways to meet the global electricity demand for ambitious climate targets and cost competitiveness, Appl. Energy 331 (2023) 120401, https://doi.org/10.1016/j.apenergy.2022.120401.
[7] J.M.F. Mendoza, A. Gallego-Schmid, A.P.M. Velenturf, P.D. Jensen, D. Ibarra, Circular economy business models and technology management strategies in the wind industry: Sustainability potential, industrial challenges and opportunities, Renew. Sustain. Energy Rev. 163 (2022) 112523, https://doi.org/10.1016/j.rser.2022.112523.
[8] D. Baldocchi, J. Penuelas, The physics and ecology of mining carbon dioxide from the atmosphere by ecosystems, Glob. Chang. Biol. 25 (2019) 1191–1197, https://doi.org/10.1111/gcb.14559.
[9] M.R. Usman, Hydrogen storage methods: Review and current status, Renew. Sustain. Energy Rev. 167 (2022) 112743.
[10] M.A. Mac Kinnon, J. Brouwer, S. Samuelsen, The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration, Prog. Energy Combust. Sci. 64 (2018) 62–92, https://doi.org/10.1016/j.pecs.2017.10.002.
[11] V. Tietze, D. Stolten, Comparison of hydrogen and methane storage by means of a thermodynamic analysis, 20th World Hydrog Energy Conf WHEC 2014 (2) (2014) 1386–1394.
[12] L. Zhong, E. Yao, H. Zou, G. Xi, Thermodynamic and economic analysis of a directly solar-driven power-to-methane system by detailed distributed parameter method, Appl. Energy 312 (2022) 118670, https://doi.org/10.1016/j.apenergy.2022.118670.
[13] L. Wang, M. Rao, S. Diethelm, T.-E. Lin, H. Zhang, A. Hagen, F. Maréchal, J. Van herle, Power-to-methane via co-electrolysis of H2O and CO2: The effects of pressurized operation and internal methanation, Appl. Energy 250 (2019) 1432–1445.
[14] M. Hervy, J. Maistrello, L. Brito, M. Rizand, E. Basset, Y. Kara, M. Maheut, Power-to-gas: CO2 methanation in a catalytic fluidized bed reactor at demonstration scale, experimental results and simulation, J. CO2 Util. 50 (2021) 101610, https://doi.org/10.1016/j.jcou.2021.101610.
[15] R. Peters, M. Baltruweit, T. Grube, R.C. Samsun, D. Stolten, A techno economic analysis of the power to gas route, J. CO2 Util. 34 (2019) 616–634, https://doi.org/10.1016/j.jcou.2019.07.009.
[16] D. Bellotti, M. Rivarolo, L. Magistri, A comparative techno-economic and sensitivity analysis of Power-to-X processes from different energy sources, Energy Convers Manag 260 (2022), 115565, https://doi.org/10.1016/j.enconman.2022.115565.
[17] D. Parra, X. Zhang, C. Bauer, M.K. Patel, An integrated techno-economic and life cycle environmental assessment of power-to-gas systems, Appl. Energy 193 (2017) 440–454, https://doi.org/10.1016/j.apenergy.2017.02.063.
[18] F. Salomone, E. Giglio, D. Ferrero, M. Santarelli, R. Pirone, S. Bensaid, Techno-economic modelling of a Power-to-Gas system based on SOEC electrolysis and CO2 methanation in a RES-based electric grid, Chem. Eng. J. 377 (2019), 120233, https://doi.org/10.1016/j.cej.2018.10.170.
[19] N. Gerloff, Levelized and environmental costs of power-to-gas generation in Germany, Int. J. Hydrogen Energy 48 (49) (2023) 18541–18556.
[20] C. Wulf, J. Linßen, P. Zapp, Review of power-to-gas projects in Europe, Energy Procedia 155 (2018) 367–378, https://doi.org/10.1016/j.egypro.2018.11.041.
[21] J. Ren, H. Lou, N. Xu, F. Zeng, G. Pei, Z. Wang, Methanation of CO/CO2 for power to methane process: Fundamentals, status, and perspectives, J Energy Chem 80 (2023) 182–206, https://doi.org/10.1016/j.jechem.2023.01.034.
[22] A. Tantau, R. Staiger, Business Models for Renewable Energy Initiatives: Emerging Research and Opportunities. 2017. https://doi.org/10.4018/978-1-5225-2688-9.
[23] Methane prices. Glob Pet Prices 2023. https://www.globalpetrolprices.com/methane_prices/ (accessed May 30, 2023).
[24] API Price Trend Dashboard - Oxygen. Pharmacompass 2023. https://www.pharmacompass.com/price/oxygen (accessed May 30, 2023).
[25] EIA. Electric Power Monthly. 2023.
[26] Industrial electricity tariff. Qatar Gen Electr Water Corp 2023. https://www.km.qa/CustomerService/pages/tariff.aspx (accessed May 30, 2023).
[27] EC. EU Emissions Trading System (EU ETS). Eur Comm 2022. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en (accessed May 30, 2023).
[28] Frøhlke U, Topsoe. Topsoe To Build World's Largest Electrolyzer Manufacturing Facility To Accelerate Power-To-X Capacity. TOPSOE 2022. https://blog.topsoe.com/topsoe-to-build-worlds-largest-electrolyzer-production-facility-to-accelerate-power-to-x-capacity (accessed February 25, 2023).
[29] Iea, Capital costs of utility-scale solar PV in selected emerging economies, Paris (2020).
[30] G. Jachin, C. van Leeuwen, F. Ortloff, Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation. 2018.
[31] Office Equipment Solutions. Mannai Trading 2023. https://mannai-ict.com/office-equipment-solutions/ (accessed February 6, 2023).
[32] Laptop and Computers. Electronyat 2023. https://electronyat.qa/en/laptops-in-qatar (accessed February 6, 2023).
[33] Atrium Interiors. Atrium Furnit 2023. https://www.artisansinteriors.qa/index.html (accessed February 6, 2023).
[34] QDB. Engineering Projects. Qatar Dev Bank 2023. https://www.qdb.qa/en/engineering-projects (accessed February 6, 2023).
[35] QFMA. Legislations - Provision for Contingencies. Qatar Financ Mark Auth 2023. https://www.qfma.org.qa/english/Pages/default.aspx (accessed February 6, 2026).
[36] Media Relations. Qommunication 2023. https://www.qommunication.co/our-work/#Services (accessed February 6, 2023).
[37] E.G. Nelson, That Balance-Sheet Approach. Account Rev 10 (1935) 313.
[38] P.A. Griffin, Financial Statement Analysis. Find. Alphas A Quant. Approach to Build. Trading Strateg., 2015, p. 119–25. https://doi.org/10.1002/9781119057871.ch22.
[39] P.M. Dechow, Accounting earnings and cash flows as measures of firm performance. The role of accounting accruals, J. Acc. Econ. 18 (1994) 3–42, https://doi.org/10.1016/0165-4101(94)90016-7.
[40] EIA. Country Analysis Brief: Qatar. 2023.
[41] Global Petrol Prices. Methane prices. Glob Pet Prices 2023. https://www.globalpetrolprices.com/methane_prices/.

[42] International Energy Agency. Putting CO2 to Use Creating Value from emissions. 2019.
[43] M.A. Rosen, S.K. Fayegh, A review of energy storage types, applications and recent developments, J Energy Storage 27 (2020) 1–23.
[44] L.P. De, F.L. Di, Y. Li, B. Stackhouse, A. Nojek, The world needs to capture, use, and store gigatons of CO2: Where and how? McKinsey Insights (2023).
[45] S. Morgenthaler, C. Ball, J.C. Koj, W. Kuckshinrichs, D. Witthaut, Site-dependent levelized cost assessment for fully renewable Power-to-Methane systems, Energy Convers. Manag. 223 (2020) 113150, https://doi.org/10.1016/j.enconman.2020.113150.
[46] J. Gorre, F. Ortloff, C. van Leeuwen, Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage, Appl. Energy 253 (2019) 113594, https://doi.org/10.1016/j.apenergy.2019.113594.
[47] J. Guilera, J. Ramon Morante, T. Andreu, Economic viability of SNG production from power and CO2, Energy Convers. Manag. 162 (2018) 218–224, https://doi.org/10.1016/j.enconman.2018.02.037.
[48] A. Abánades, Natural gas decarbonization as tool for greenhouse gases emission control, Front. Energy Res. 6 (2018), https://doi.org/10.3389/fenrg.2018.00047.
[49] C. Choe, B. Lee, A. Kim, S. Cheon, H. Lim, Comprehensive assessment of CO2 methanation: Which H2 production pathway is practicable for green methane production in terms of technical, economic, and environmental aspects? Green Chem. 23 (2021) 9502–9514, https://doi.org/10.1039/d1gc02755g.