Stanford University

Hydrogen Garbage Trucks for Palo Alto:

A Financial, Environmental, and Policy Analysis

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I. Executive Summary

The City of Palo Alto's mission is simple: to promote and sustain a high quality of life in Palo Alto. From the first inhabitants of the Ohlone tribe to over 65,000 in current population, the city has a record of delivering cost-effective services in a responsive, personal, and innovative manner. Within the Public Works Department, a key responsibility is the maintenance of the city fleet. The current curbside collection services offer recycling, compost, and landfill pickup for the community. And in order to deliver these services, the City of Palo Alto is reliant on 30 garbage trucks, 28 powered by diesel and 2 by battery electric. This is where hydrogen cell fuel comes into the picture, offering an eco-friendly but costly alternative. With evolving regulations and increased demand for sustainable operations, the City of Palo Alto reached out to the Stanford Management Science and Engineering (MS&E) Department to spearhead analysis on this matter. The problem is that there is a lack of financial strategy and environmental analysis on fleet management in the City of Palo Alto, which hinders the investment decision on hydrogen-powered garbage trucks.

As Stanford seniors studying MS&E, our team of four decided to apply as many key principles, frameworks, and learnings from our undergraduate curriculum to tackle this problem. The core methodologies guiding our decision stem from the following:

(1) **Decision Quality Framework** to assess the fundamental decision, alternatives, uncertainties, and values

(2) **Comparative Cost Analysis** to standardize fuel costs and compute total cost of ownership

(3) **Environmental Impact Framework** to analyze life cycle of carbon emission and introduce a Sustainable Return on Investment (SROI) model

(4) **Regulatory and Political Analysis** to assess Federal policy shifts and California's Hydrogen/ZEV Policy

(5) **20-Year Scenario Analysis** to aggregate methods 1 - 4 and weigh investment decisions

After conducting the 20-Year Scenario Analysis, we advise that the City of Palo Alto consider the following recommendations:

(1) **Invest** gradually in more hydrogen trucks to align with long-term sustainability goals and evolving regulations. This ensures a scalable transition while mitigating financial and operational risks.

(2) **Cease** further investments in diesel trucks due to their declining cost-effectiveness, increasing regulatory restrictions, and long-term environmental impact.

(3) **Leverage** policy incentives and emerging technologies to optimize the cost-benefit ratio and ensure a smooth transition.

II. Introduction

A. Background on the City of Palo Alto

Since 1894, the **City of Palo Alto** has been serving businesses and communities in the heart of Silicon Valley, California. More specifically, the *Public Works Engineering Department* is responsible for budgeting, designing, and managing the city's infrastructure. The Public Works Department's mission is to provide quality services with commitment, courtesy, and pride. Each project and initiative is executed in close partnership with the Palo Alto community to make the city a beautiful, safe, and comfortable place to live and work. For example, the city's Infrastructure Plan began in 2014, beginning with nine projects in the form of a new public safety building, two parking garages, two fire stations, and a bike and pedestrian roadmap. Now,

costing $270 million, the city recognizes the urgency of focusing on transportation and fleet operations (“Infrastructure Plan: City of Palo Alto, CA”). According to the U.S. Environmental Protection Agency, transportation is responsible for 28% of total US GHG emissions, with diesel vehicles being the primary contributor (“Fast Facts on Transportation Greenhouse Gas Emissions”).

Given this information, Phil Bobel (prior Manager of Public Works Engineering) and Brad Eggleston (Director of Public Works) have brought this investment decision to the MS&E 108 Hydrogen Team. Our sponsor has entrusted the team to provide a decision-making framework by assessing the uncertainties, alternatives, values, and challenges in the dilemma. The areas of focus can be boiled down to three buckets: cost, environmental impact, and regulation and policy. We hope to bring Brad Eggleston, our Decision Maker (DM), valuable recommendations through the decision quality, competitive cost analysis, and environmental impact framework.

For financial costs, we assess both capital and operational costs to give the city a holistic view of how much to invest over a given period of time. It will also look at the cost of investment up-front, during, and post-implementation of the pilot. The DM is focused on sustainable practices from industrial manufacturing and fleet operations associated with different trucks in Palo Alto. Currently, there are trade-offs for both electric and hydrogen trucks, so we want to assess which will be best in terms of cost and carbon emissions. Heavy-duty trucks for garbage picking and other purposes are mostly fueled by petroleum diesel. By 2027, all new public fleets purchased are required to be ZEVs and by 2036, all medium and heavy duty trucks sold must be ZEVs (“CARB Unveils Advanced Clean Fleets Rule to Combat Vehicle Pollution”). For this reason, the City of Palo Alto is looking to introduce electric, hydrogen, or a

combination of both into the Public Work Engineering's fleet. Our project will help the City of Palo Alto decide which energy-fueled garbage trucks would be the most optimal investment. Understanding the carbon footprint of trucks at different stages in their life cycle could greatly influence decisions made by Phil and the City of Palo Alto. If piloted successfully, there are key opportunities that open up for the city. Some of these include long-term cost savings, significant GHG reduction, and public-private partnerships.

B. Key Stakeholders in the Pilot

The stakeholder engagement strategy for the pilot follows a structured approach, beginning with peer-level connections across city staff, GreenWaste representatives, and the public to establish early buy-in and gather insights. Once initial alignment is achieved, the focus shifts to securing support from key department heads, including Brad Eggleston (Director of Public Works), Lauren Lai (CFO of Administrative Services), and Molley Stumph (Head of the Attorney's Office), ensuring financial feasibility and legal compliance. Simultaneously, GreenWaste must be engaged to confirm operational readiness and driver comfort with the new trucks. With departmental alignment in place, outreach expands to city leadership, including the City Council and the mayor, alongside public engagement efforts through sustainability groups like the Zero Waste mailing list. The final step is securing City Council approval by presenting a well-supported case demonstrating financial viability, operational feasibility, and strong public backing, ensuring a smooth path toward implementation.

C. Failed History in Launching Hydrogen

To further understand the City of Palo Alto's dilemma, we can examine their failed history in launching hydrogen-fueled trucks. Many of the bottlenecks and delays in this

investment decision can be attributed to Hyzon's records. Hyzon was a hydrogen fuel cell technology manufacturer with the mission of delivering zero-emission power to decarbonize demanding industries. In January 2024, they delivered four hydrogen FCEV trucks in Fontana, CA, which was a significant milestone for fuel cell-powered refuse trucks. The company was promising until it could no longer be strategically sustainable. With a CEO switch in 2022 and dwindling product iteration speeds, Hyzon could not keep up with customer demand. In January 2025, the Hyzon board voted to dissolve the company, as it had burned through nearly $25 million in Q3 (Hyzon CEO resigns as company nears dissolution, 2024).

GreenWaste is a solid waste and recyclables processor based in San Jose, California. With the mission of focusing on innovation, people, and the commitment to be green first, GreenWaste seeks to revolutionize how they transform the world's waste. In 2023, they reported a 36.3% reduction in total combined Scope 1 and Scope 2 emissions from their 2022 baseline. By 2030, they are working to reduce Scope 1 and Scope 2 emissions by 45% (GreenWaste 2023 Sustainability Report, 2023). GreenWaste has also been at the forefront of green transportation, which is why we want to consider them a potential partner. Since 2023, they have adopted and completed a transition to 100% zero-emission vehicles (ZEVs).

The fleetwide change could not have happened overnight. In 2017, GreenWaste of Palo Alto (GWPA) piloted its all-electric, side-loading refuse truck. The first iteration of these trucks were predominantly used in a residential Clean Up program—bin and cart deliveries, commercial bin washes, etc. GWPA closely collected data on the truck's maintenance, reliability, and longevity. By 2020, they saw that this electric truck saved approximately 6,000 gallons of diesel per year and reduced carbon emissions by approximately 78 metric tons of CO2 annually

(Collection Goes Electric, 2023). The deployment of electric trucks was evidently cost-efficient, so why did they launch a second iteration of the trucks with increased battery and mileage.

Tracy Adams, the CEO of GreenWaste, plays a key role in this project as he approaches hydrogen-powered trucking from a business lens. In the past, it has been extremely difficult for hydrogen trucks to be a viable product. This comes with investment challenges and incomplete business plans, making hydrogen-powered fleets an intense initiative. Our team will take GreenWaste's expertise to fill the gaps for the City of Palo Alto.

D. Constraints in Climate and Regulation

Climate change and evolving regulation serve as a constraint when influencing an investment decision on hydrogen-powered trucks. Given that the City of Palo Alto highly values sustainability, the city is reluctant to pilot a truck with an under-researched fuel source as its outcomes are unclear. The impacts of climate change can be extremely harmful to our society and are driven by humans. For this reason, a key metric we will factor into our Sustainable Return on Investment (SROI) model is the Social Cost of Carbon (SCC) which quantifies the economics hard caused by each metric ton of carbon dioxide in the atmosphere. By considering the economic impacts of CO2 emission in our analysis, we aim to tangentially factor in health impacts and civilian well-being. Currently, the lack of environmental impact analysis can be attributed to changing political SCC estimates in dollars per ton. We see this in the notable variance between the Trump and Biden administrations, primarily due to political priorities. Moreover, the following literature review and frameworks will approach climate change from an adaptable perspective, accounting for the complexities of environmental, economic, and social dynamics.

III. Literature Review

A. Case Studies

Studying prior hydrogen initiatives in the Bay Area serves as a good navigation tool for our research. We will evaluate the process, launch, and results of Recology's pilots and the NorCAL Zero project. However, the majority of pilots in recent years have reported qualitative outcomes with emphasis on operational feasibility rather than long-term sustainability. Since the pilots require partnerships with truck manufacturers, hydrogen fuel cell developers, and city partners, the follow-through from city-wide projects is unclear. The following case studies hope to synthesize the current standing of hydrogen and electric trucks.

In May 2024, NorCAL Zero was a $53 million initiative to deploy 30 Hyundai XCIENT Class 8 hydrogen fuel cell electric trucks (FCETs). This Hyundai truck was the world's first commercialized fuel cell heavy-duty truck with a singular truck being able to travel over 400 miles from a singular cell (Port of Oakland celebrates hydrogen-powered trucks project, 2024). Although no data following the deployment was released, it replaced diesel-powered cargo handling in the Port of Oakland, which can be seen as a positive effort toward climate consciousness.

Recology is a private waste collection company with the mission of representing a fundamental shift from traditional waste management to resource recovery. Debuting in San Francisco in August 2024, Recology piloted the city's first hydrogen-powered refuse collection (Recology testing hydrogen-powered refuse trucks in San Francisco, 2024). New Way Trucks built the truck's body and Hyzon developed the hydrogen fuel cell for this pilot. Recology also wanted to test out the truck on different terrains while continuing to measure its impacts. In

September 2024, they were contracted for a landfill collection project in Redwood Shores for San Mateo County (North America's first hydrogen-powered garbage truck debuts in Redwood Shores: cleaner, but costly, 2024). They reported that the hydrogen-powered garbage trucks were significantly more comfortable and quieter to drive. However, the hydrogen production itself still produced some carbon lifecycle emissions, not to mention its extremely high costs.

B. The UN Sustainable Development Goals

In 2015, all the United Nations Member States adopted the 2030 agenda for sustainable development. The goal of this agenda was to provide a framework for peace and prosperity for the planet and the people who inhabit it, starting now and continuing onwards in the future. The 17 Sustainable Development Goals (SDG) is a call to action to work towards creating a better world in terms of health, economics, education, equalities, and climate across the globe. The UN Secretary General will present an annual SDG progress report (dating back from 2016) to ensure that these goals are being implemented and tracked accordingly.

Of the 17 Sustainable Development Goals, several goals pertain to this project and the overall goal of being more environmentally conscious. These goals revolve around clean energy, industrial innovation, sustainable cities, strong health, and climate action. SDG 3 is good health and well-being. The goal is to ensure healthy lives and promote well-being for all at all ages United Nations, n.d.). SDG 7 is to ensure access to affordable, reliable, sustainable and modern energy for all. This aligns with the project when examining hydrogen and electric fuel options for refuse trucks (United Nations, n.d.). SDG 9 revolved around industry, innovation, and infrastructure. The overall goal in this area is to build resilient infrastructure, promote inclusive, and sustainable industrialization and foster innovation. This goal aligns with the City of Palo Alto as it promotes innovation with cleaner vehicles for a better city infrastructure (United

Nations, n.d.). SDG 11 is about sustainable cities and communities. The overarching goal is to make cities and human settlements inclusive, safe, resilient and sustainable. Moving from diesel to a cleaner fuel source, we create more sustainable cities with cleaner air and reduced emissions (United Nations, n.d.). Finally, SDG 13 is climate action with the goal to take urgent action to combat climate change and its impacts. This goal directly aligns with this project as electric and hydrogen fuel sources will reduce transportation related and overall emissions (United Nations, n.d.).

Overall, these goals reveal how the world is moving forward to become more sustainable and healthy. These goals provide a framework for driving sustainable decision-making in areas such as green technologies, climate action, and planetary health. Although these are global goals, change starts in local communities such as Palo Alto. The city plays a crucial role in adopting more sustainable practices and financial investments that are aligned with these global overarching goals.

C. Competitive Resources

Following our Environmental Analysis, the City of Palo Alto, in collaboration with GreenWaste, aims to identify the most efficient, cost-effective, and sustainable waste management solution. Due to the significant environmental impact of diesel-powered garbage trucks, Palo Alto is committed to transitioning to zero-emission vehicles. Currently, the city has six potential fuel options: diesel, biodiesel, compressed natural gas (CNG), renewable natural gas (RNG), electricity, and hydrogen. Each alternative comes with its own benefits and challenges.

To determine the best option for Palo Alto, our analysis includes:

- A cost analysis supported by visual charts

- A life cycle assessment of each fuel type, examining both financial and carbon costs
- A cumulative cost projection over the next 10–25 years, incorporating acquisition, operational, and maintenance expenses

D. Incentives, Regulations, and Policy

The federal and state policy regulations and financial incentives around hydrogen and zero-emission vehicles (ZEVs) are an important factor in evaluating the feasibility of hydrogen-powered garbage trucks for Palo Alto. Having a deep understanding of the policy angle will help us determine how Palo Alto can leverage existing financial and legislative mechanisms to support their potential transition to hydrogen.

First, let us consider what we know so far. On a state level, California's Advanced Clean Trucks (ACT) regulation, mandated that by the end of 2024, 5% to 9% of sales, depending on the truck category, needed to be ZEVs. By 2035, all new medium-to-heavy duty truck sales are required to be ZEVs, and by 2045, all such vehicles on the road must be zero-emission. However, in January 2025, the California Air Resources Board (CARB) withdrew its request for a federal waiver to enforce the Advanced Clean Fleets (ACF) regulations, anticipating challenges under the current federal administration and introducing uncertainty regarding the enforcement of zero-emission mandates. In terms of incentives, the Inflation Reduction Act (IRA) of 2022 introduced the Clean Hydrogen Production Tax Credit (Section 45V), offering up to $3.00 per kilogram of clean hydrogen produced, which could impact Palo Alto fleets. On a state level, the Carl Moyer grant program provides grants to public fleets to fund the cost of switching from diesel to ZEV fuels like hydrogen, and it was just announced that electric vehicles will no longer be eligible for this, further incentivizing the switch to hydrogen. This was a program mentioned by Tracy Adams, the CEO of GreenWaste, who we spoke with as discussed earlier. Tracy also

noted that, in his view, the new federal government is much less hydrogen-friendly; however, California-specific policies should be relatively unaffected due to the state's large influence and ambitious attitude with regard to ZEVs.

IV. Methods

A. Decision Quality Framework

1. Decision Maker's (DM) Dilemma

The Decision Quality Framework is extracted from *MS&E 152: Introduction to Decision Analysis*, where we learned how to make great decisions in a complex, dynamic, and uncertain world. To outline a structure approach, we obtained clarity of action in a wide variety of domains, beginning with our Decision Maker's (DM) dilemma. Our DM, Brad Eggleston, is the Director of Public Works focused on potentially piloting a hydrogen-powered garbage truck for the City of Palo Alto. Brad Eggleston plays a critical role in evaluating, approving, and implementing major infrastructure and sustainability-related investments, where he makes a decision based on various perspectives. As represented in the stakeholder diagram, the dilemma comes down to a multi-faceted investment decision, aggregating data points and

drawing conversation from the general public, City Staff, GreenWaste, and hydrogen suppliers.

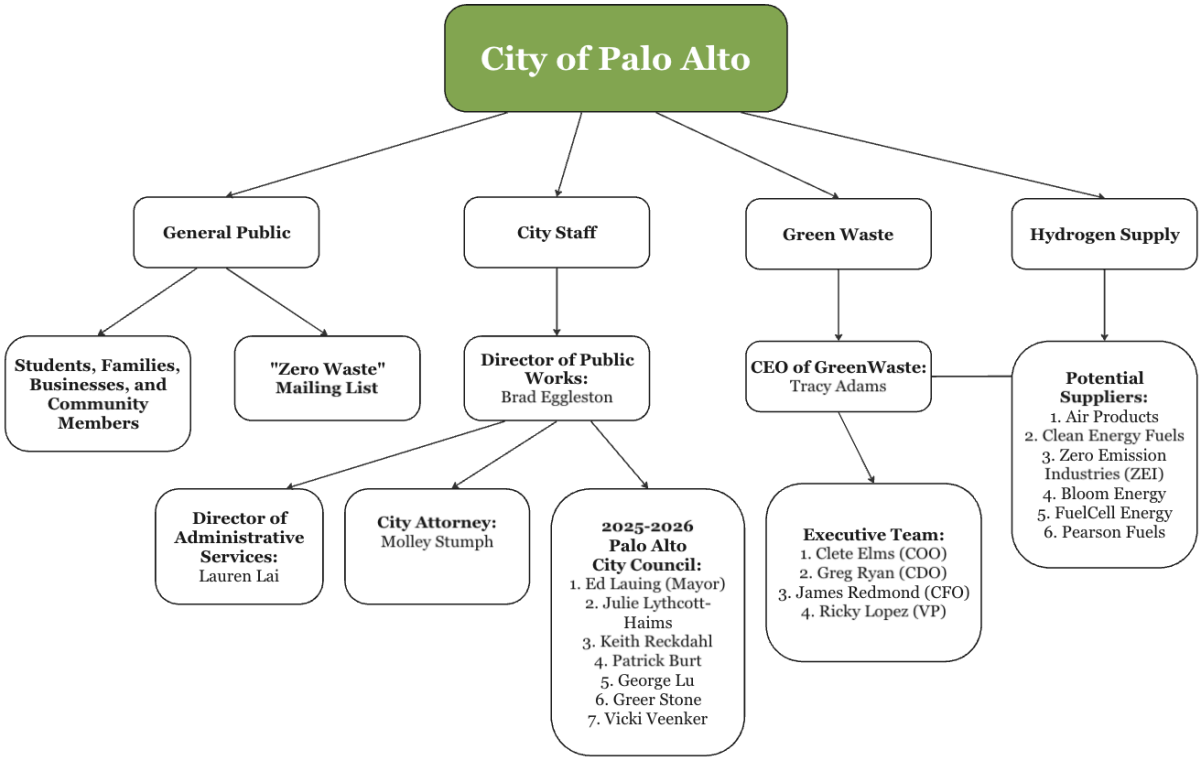


Figure 1.A: Stakeholder Diagram for the City of Palo Alto

2. Components of Decision Quality

The main components of decision quality can be put into four buckets: fundamental decision, alternatives, uncertainties, and values. For the City of Palo, we applied decision analysis techniques to inform whether an investment in hydrogen-powered trucks would be cost-effective, sustainable, and legally compliant. The DM needs to decide between electric trucks, hydrogen trucks, or a combination of all three. If a hydrogen pilot is selected, the alternative would account for the refuse truck collection and hydrogen supplier that will be essential to launch the pilot. The chosen strategy must demonstrate a net-positive impact on the city while accounting for the constraints of the pilot. Moreover, we performed the analysis with several uncertainties:

- Product-Market Fit: Even with the recent $53 pilot in Oakland, there is a lack of transparent data or news on the success of these trucks. Since Hyzon proved unsuccessful, we need to understand if hydrogen trucks would be a feasible and smart investment in Palo Alto's fleet.
- Accurate Carbon Emission: With NDAs in place between GreenWaste and bankrupt company Hyzon, there are minimally accessible datasets to make accurate predictions on environmental impact.
- Commitment of Local Partners and Stakeholders: With the Board of Hyzon recently disbanding, we are skeptical on how much traction there will be around this pilot.

Another key component of the decision quality is the DM's values, in other words, what the DM cares about. Some of the values and our their weighted importance are below:

- Sustainability (Quality): To provide high-quality and sustainable services (0.5)
- Courtesy: To provide services with respect and concern (0.1)
- Efficiency: To use resources effectively and sustainably (0.3)
- Integrity: To maintain honest, fair, and straightforward relations (0.1)

From the values listed, we know our DM cares most about efficiency and sustainable outcomes as they align clearly with the goal of potentially getting a hydrogen truck rolling in the streets of Palo Alto. The DM, on behalf of the Public Works Department, wants to know where to source a fuel-cell electric vehicle (FCEV) and hydrogen.

3. Decision Basis Assessment

In the Decision Basis Assessment, we created an inference diagram taught in MS&E 152 to map out possibilities, relevance, value of information, and risk attitude in regards to the dilemma. The DM

observes that there are certain qualities that makes the City of Palo Alto fit to launch a hydrogen truck pilot:

- What are the capital and operational costs of the pilot? In the short-run? In the long-run?
- Will the pilot divert 95% of waste from landfills by 2030?
- How will state/national regulations support or prohibit the execution of this pilot?

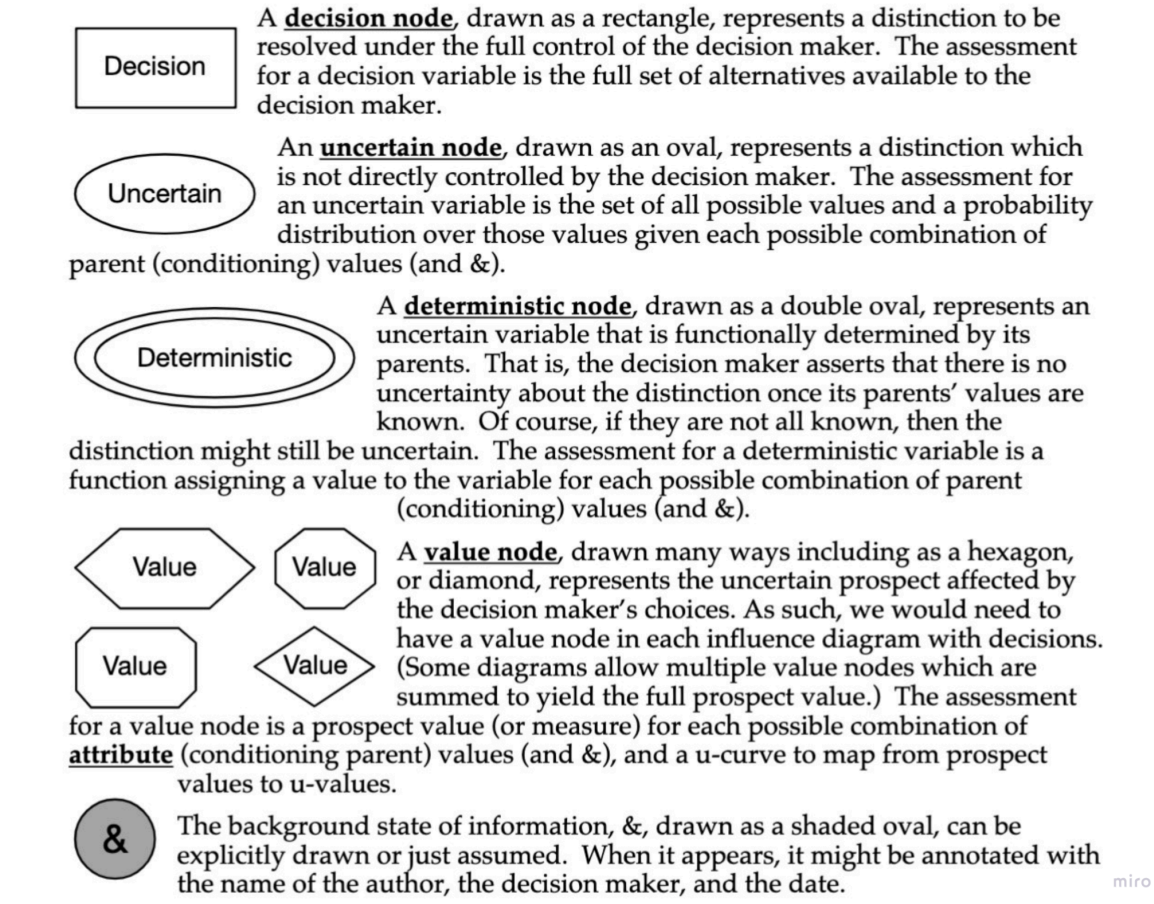


Figure 2.A: Decision Quality Dictionary

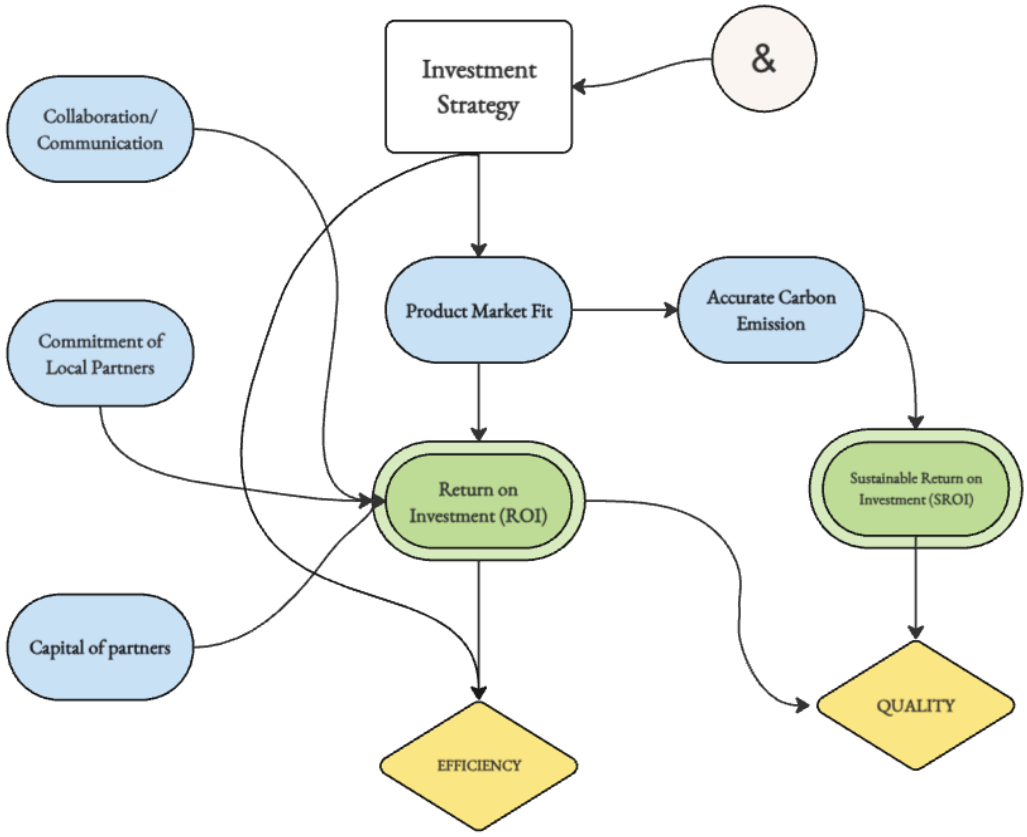


Figure 2.B: Influence Diagram for the Decision Quality Framework

Before diving into the competitive cost and environmental impact framework, we approach the decision quality framework from a high level. Each alternative, namely hydrogen, electric, or a hybrid approach, can be scored based on these weighted criteria:

Criteria	**Hydrogen**	**Electric Trucks**	**Hybrid Approach**
Initial Cost	High (+)	Medium (o)	High (+)
Long-Term Savings	Medium (o)	High (+)	Medium (o)
CO2 Emission Reduction	High (+)	High (+)	High (+)

Infrastructure Readiness	Low (-)	Medium (o)	Medium (o)
Regulatory Support	Medium (o)	High (+)	High (+)
Operational Feasibility	Medium (o)	High (+)	Medium (o)

Table 1.A: Hydrogen vs. Electric vs. Hybrid Pilot Approach

Legend: Disadvantage (-), Neutral (o), Advantage (+)

To prepare for a decision-based assessment in making the most suitable refuse truck solution for Palo Alto's fleet, we have to examine significant factors such as feasibility, cost-effectiveness, sustainability impact, and infrastructural readiness. This assessment should include a comparison of hydrogen truck upfront and operating expenditures versus electric counterparts, assessment of state and national incentives to decarbonize fleets, and an assessment of the availability of hydrogen fueling infrastructure. We must also get together with would-be suppliers, New Way Trucks for garbage truck collection vehicles and Clean Energy Fuels, Bloom Energy, and Zero Emission Industries for supply of hydrogen, to find out their capacity, fees, and longevity in the future. Carrying out a pilot study with clear performance metrics, including cost per mile, maintenance requirements, and emission savings, will provide critical information to determine whether hydrogen is a strategic and feasible investment for Palo Alto's sustainable waste management practices.

B. Comparative Cost Framework

1. Alternative Fuel Sources

One of the first challenges we encountered was the difficulty of comparing fuel types due to their varying states as some are liquid, others gaseous, and electricity is neither. Additionally, these fuels are measured in different units: electricity in watts (W), hydrogen by mass (kg), CNG and RNG by energy content in gasoline gallon equivalents (GGE), and diesel and biodiesel by volume (liters). To address this complexity, we standardized our measurements by equalizing the energy output of each fuel type. This standardized output is called the Diesel-Equivalent Gallon (DEG). The table below presents the consolidated metrics.

Fuel Type	**Energy Content per Respective Unit**	**Fuel Sources to Diesel-Equivalent Gallon (DEG)**
Diesel	128,488 BTU/gallon	1 gallon
Biodiesel (B100)	119,550 BTU/gallon	1.08 gallons
CNG	114,000 BTU/GGE	1.13 GGE
RNG	114,000 BTU/GGE	1.13 GGE
Electricity	3,414 BTU/kWh	37.64 kWh
Hydrogen	51,532 BTU/lb	2.49 lbs

Table 2.A: Standardized Unit for Fuel Type

It must be noted that Diesel serves as the baseline with an energy content of 128,488 BTU per gallon. A British Thermal Unit (BTU) is a measure of energy, defined as the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit. Biodiesel (B100) contains approximately 119,550 BTU per gallon, requiring about 1.08 gallons to match the energy content of one gallon of diesel. Compressed Natural Gas (CNG), which is measured in Gasoline Gallon Equivalents (GGE), with 1 GGE equating to 114,000 BTU, requires approximately 1.13 GGEs to equal the energy in one gallon of diesel. Renewable Natural Gas (RNG) shares the same energy content as CNG. Electricity, with 3,414 BTU per kilowatt-hour (kWh), takes about 37.64 kWh to match the energy content of one gallon of diesel. Lastly, hydrogen should weigh approximately 2.49 pounds (lbs) to equal the energy content of one gallon of diesel. Going forward, most of our analysis will try to standardize our prices, costs, and quantities when making comparisons between different sources of fuel. For that reason, any reference to the Diesel-Equivalent Gallon refers to this table for each of its respective fuel-types.

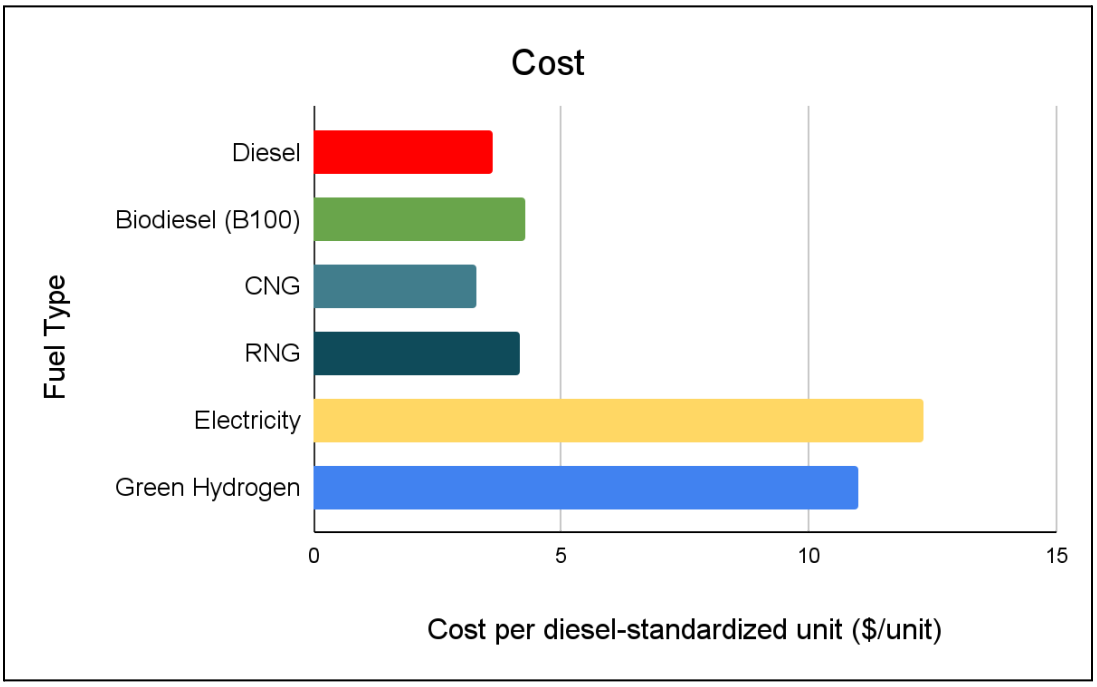


Figure 3.A: Fuel Type Costs in DEG

With these standardized metrics, we can better understand the relative costs of each fuel type when adjusted for their energy equivalence to diesel. The cost-adjusted DEG provides a clear comparison of affordability, revealing significant discrepancies between fuel options. As shown in the cost analysis chart, diesel and CNG remain the most cost-effective, with biodiesel and RNG also offering relatively low-cost alternatives. However, hydrogen (specifcally green hydrogen) presents a notable increase in cost per diesel-equivalent unit, while electricity far exceeds all other fuels, making it the most expensive option. We observe that electricity and green hydrogen cost close to 2-3 times more than diesel. With environmental and health considerations in mind, the next phase of our analysis will focus on the long-term financial implications of each fuel type.

II. Cumulative Cost Production and Options

A cumulative cost prediction over the next 20 years will evaluate the total cost of ownership, factoring in fuel prices, capital costs, and inflation. Additionally, a Scenario Analysis will assess different adoption pathways carefully examining potential regulatory changes, fuel price fluctuations, and technology advancements to determine the most financially and environmentally sustainable strategy for Palo Alto's waste management fleet.

A separate, but vitally relevant, solution being discussed is the acquisition of hybrid trucks. On first thought, that seems a great idea, as it would help the city roll out their carbon-neutral alternatives, while still providing them the comfort of reliability and trust in their trucks. If the City of Palo Alto and its waste management partner, GreeenWaste, replace their trucks every seven years, investing in hybrid trucks (vehicles that combine diesel, electric, and/or hydrogen power) would present significant challenges compared to adopting a hybrid fleet with

separate electric, hydrogen, and biodiesel trucks. A primary concern is the increased complexity and cost of maintenance. Hybrid trucks with multiple powertrains would require servicing expertise in diesel engines, electric battery systems, and hydrogen fuel cells, leading to higher training costs, specialized parts inventory, and more frequent maintenance due to the interplay of different technologies. Given that each truck would only be in use for approximately seven years, the additional costs of maintaining and repairing hybrid trucks would likely outweigh the benefits, making a hybrid fleet (where each truck is designed for a specific fuel source) a more practical and cost-effective approach.

Furthermore, a hybrid fleet, as opposed to a fleet of hybrid trucks, aligns more effectively with Palo Alto's long-term sustainability goals. The city aims to be carbon-neutral by 2035, and California's Advanced Clean Fleets regulation mandates that all new medium- and heavy-duty trucks sold by 2036 must be zero-emission vehicles (ZEVs). Purchasing hybrid trucks that still rely partially on diesel would render them obsolete within one fleet cycle, requiring another costly transition before the deadline. Instead, gradually integrating electric and hydrogen trucks while phasing out diesel ensures a smoother transition without prematurely retiring vehicles. Financially, this approach is more sustainable, allowing the city to make targeted investments in new technologies while avoiding unnecessary expenditures on hybrid trucks that would soon be outdated.

Ultimately, rather than investing in hybrid trucks with multiple fuel sources, Palo Alto should adopt a hybrid fleet approach, where each truck is optimized for a specific energy source. This strategy minimizes maintenance complexity, reduces investment costs, and ensures a steady transition toward a fully zero-emission fleet by 2035.

2. Fuel Emissions Comparison

Beyond financial considerations, assessing the environmental and health impacts of fuel choices is critical, particularly given Palo Alto's commitment to sustainability and public health. While CO_2 emissions remain a key metric in evaluating climate impact, other pollutants, such as nitrous oxides (NO_x) and particulate matter (PM10), also play a significant role in urban air quality and community health. Heavy-duty diesel trucks, commonly used in waste management, emit substantial amounts of NO_x and PM10, contributing to respiratory issues, cardiovascular diseases, and overall reduced air quality.

Fuel	**CO_2 [lbs/mile]**	**NO_x [lbs/mile]**	**PM_{10} [lbs/mile]**
Diesel	0.49	8.4×10^{-4}	1.1×10^{-5}
CNG	0.51	3.2×10^{-5}	0

Table 3.A: Diesel vs. CNG Emissions

As seen in Table 3.A, a study done by the UN Climate Technology Centre and Network shows that diesel combustion produces significant levels of CO_2, NO_x, and PM10, reinforcing concerns about its long-term viability. Comparatively, CNG shows slightly higher CO_2 emissions per mile than diesel but significantly lower NO_x and PM10 emissions, making it a cleaner alternative for air quality. However, research suggests that not all CNG technologies yield the same benefits. Lean-burn CNG engines, which operate with excess air for better fuel efficiency, produce similar NO_x emissions to diesel, offsetting some of their environmental advantages. On the other hand, stoichiometric CNG engines, which maintain a precise oxygen-to-fuel ratio, emit up to 60% less NO_x than diesel, though at the cost of 22% higher tailpipe CO_2 emissions.

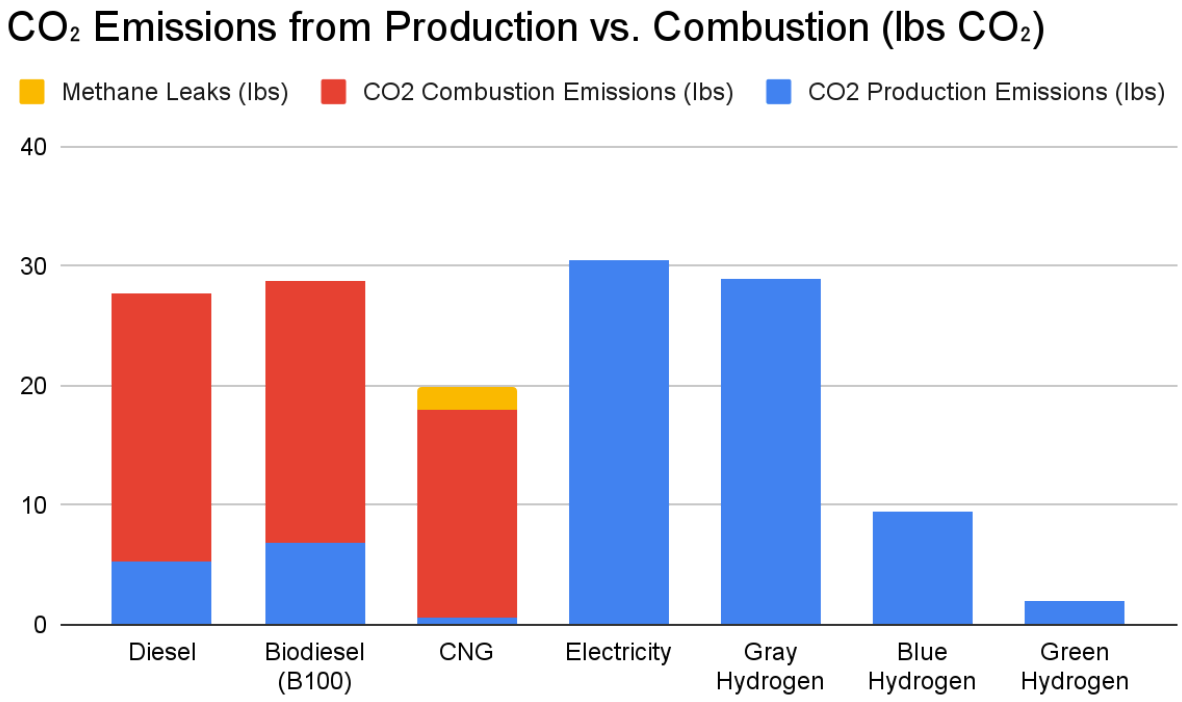


Figure 4.A: Fuel Type vs. Production and Combustion CO_2 Emissions (in lbs)

Further analyzing the environmental impact of each fuel type, **Figure 4.A** illustrates the CO_2 emissions associated with both fuel production and combustion. While traditional diesel exhibits high direct combustion emissions, biodiesel reduces tailpipe CO_2 but carries notable production emissions due to its feedstock cultivation and refining process. CNG, despite lowering particulate and NO_x emissions, shows methane leakage during production, a concern given methane's high short term global warming potential. Electricity, often considered a clean alternative, presents significant production-related CO_2 emissions depending on the energy mix powering the grid. Hydrogen, meanwhile, shows a stark contrast between gray hydrogen, which has substantial production emissions due to steam methane reforming (SMR), and green hydrogen, which remains the only fully carbon-free option but is not yet widely available at scale. This breakdown underscores the complexity of fuel selection, not just in terms of tailpipe

emissions but also in the full lifecycle impact, reinforcing the need for a holistic approach in determining the best path forward for Palo Alto's waste management fleet.

3. Rethinking Options

When we first set out to explore alternative fuel options for Palo Alto's waste management fleet, we were optimistic. The idea of cleaner-burning fuels, especially ones that could immediately lower emissions while keeping costs manageable, seemed like the perfect bridge to a zero-emission future. But as we dug deeper, we began to understand that not all "cleaner" fuels are created equal. Some, like compressed natural gas (CNG) and renewable natural gas (RNG), offered moderate emissions reductions but introduced significant infrastructure and leakage concerns. Others, like biodiesel (B100), carried impressive lifecycle carbon reductions but still relied on combustion-based energy which is a direct conflict with the city's long-term goal of full decarbonization by 2035. To make a meaningful recommendation, we needed to critically examine each fuel's viability not just in theory, but in the real-world constraints Palo Alto faces.

i. Biodiesel: How much better than Diesel?

Biodiesel is often praised as the eco-friendly twin of diesel, a renewable fuel derived from plant oils and animal fats. On paper, it seems like an ideal compromise: according to Argonne National Laboratory, lifecycle emissions of B100 are 74% lower than petroleum diesel, and because its carbon comes from recently grown biomass, rather than ancient fossil deposits, it is considered carbon-neutral in theory. But theory doesn't always translate to practice.

From a combustion standpoint, biodiesel does emit less particulate matter (PM10) and zero sulfur oxides (SOx), making it a far cleaner-burning fuel than conventional diesel. However, the CO_2 problem isn't eliminated, it's just delayed. While the CO_2 released at the tailpipe may eventually be offset by future soybean or palm oil crops, it doesn't change the fact that B100 still emits a significant amount of CO_2 when burned. More importantly, Palo Alto's goal isn't to just lower emissions, it's to eliminate them.

Then there's the issue of feedstock dependency. Large-scale biodiesel production competes with food agriculture, and the process of growing, refining, and transporting biodiesel still relies on fossil fuels. According to NREL, producing 1 liter of biodiesel emits 0.76 kg of CO_2 before it ever reaches a truck's fuel tank. When scaling up to a municipal fleet, this additional carbon cost starts to erode biodiesel's environmental advantage.

And as Phil Bobel pointed out, it's simply not the solution. Biodiesel may be better than petroleum diesel, but better isn't good enough for a city that is fully committed to a zero-emission future.

ii. CNG & RNG: The Problem of Leaks and Infrastructure

Compressed natural gas (CNG) and its renewable counterpart (RNG) are often marketed as low-emission alternatives to diesel, with lower NO_x and particulate emissions. At first glance, they seem promising, especially since RNG can be derived from landfill waste, capturing methane that would otherwise be released into the atmosphere. But as we examined the full picture, CNG and RNG revealed some hidden liabilities that made them less viable.

CNG and RNG are composed mostly of methane, which is 80 times more potent than CO_2 over a 20-year period. According to the Alvarez et al. study, the natural gas supply chain leaks 2.4% of its methane during production, processing, and distribution. That doesn't sound

like much until you realize that methane's warming potential is exponentially greater than CO_2's. The climate impact of these leaks can be so severe that switching from diesel to natural gas vehicles can actually increase near-term global warming for the next 80 to 280 years before any net climate benefits are realized (Alvarez et al., 2012).

While CNG and RNG produce fewer particulates and sulfur oxides, their nitrogen oxide (NO_x) emissions depend on engine type. It was pointed out that lean-burn CNG engines still produce NO_x emissions comparable to diesel, meaning they provide no meaningful air quality benefits. While stoichiometric CNG engines can reduce NO_x by up to 60%, this comes at the cost of 22% higher CO_2 emissions, making it a trade-off rather than a solution (MIT Climate, 2023).

Switching to CNG or RNG would require significant infrastructure investment, including fueling stations and storage facilities. Palo Alto does not currently have a CNG refueling network, meaning the city, or their partner GreeWaste, would need to invest millions into new infrastructure for a fuel that still emits carbon. If Palo Alto is going to spend money on fueling infrastructure, it makes far more sense to invest in technologies that align with a fully zero-emission future, such as electricity or green hydrogen.

For these reasons, despite its moderate emissions benefits, CNG (and RNG) is not a viable solution for Palo Alto's long-term sustainability goals.

iii. Hydrogen: The Distant Dream

At the opposite end of the spectrum is hydrogen, a fuel that (if made from renewable sources) can be completely emissions-free. In theory, hydrogen is the holy grail of sustainable energy: it burns cleanly, leaving only water vapor as a byproduct. However, as we quickly realized, the reality of hydrogen is far more complicated.

Hydrogen Type	Global Production	Production Method	CO_2 Emissions
Gray Hydrogen	95%	Natural gas (SMR)	High
Blue Hydrogen	4%	SMR + Carbon Capture Storage	Moderate
Green Hydrogen	1%	Electrolysis with renewables	None

Table 4.A: Various Hydrogen Production Methods

Most hydrogen today isn't "green." In fact, over 95% of the world's hydrogen is produced using fossil fuels (primarily through steam methane reforming), which emits large amounts of CO_2 (MIT Climate). Green hydrogen, produced by electrolysis using renewable energy, accounts for less than 1% of total hydrogen production worldwide. That means that for hydrogen to be a viable fuel alternative, the world needs to scale up production by more than 100 times its current capacity. The benefit for the City of Palo Alto however, is that the state of California has sources that offer Hydrogen and hydrogen fuel cell technology already. Guaranteed that the hydrogen is not green, it is still a start at least to enable the City of Palo Alto, and Greenwaste to pilot a couple of hydrogen-powered garbage trucks in the medium term.

Additionally, hydrogen is also extremely difficult to store and transport. Unlike gasoline or even natural gas, hydrogen must be compressed at extremely high pressures or liquefied at -253°C, requiring specialized equipment and infrastructure. There are currently no hydrogen refueling stations in Palo Alto or Santa Clara (which is the docking station for all of Palo Alto's and GreenWastes' garbage trucks), meaning a full-scale hydrogen fleet is not feasible without a massive investment in infrastructure. This infrastructure would either look like a private hydrogen fueling station near the docking station in Santa Clara, or an infrastructure to procure

and transport hydrogen to Santa Clara, both of which can be expensive in the longterm.

At current prices, green hydrogen is 3-5 times more expensive than diesel on a per-mile basis (MIT Climate). While costs are expected to drop over the next few decades, hydrogen remains expensive, at least in the short term.

With all these factors in mind, we made the decision to exclude biodiesel, CNG, and RNG from further analysis. While they each offer certain benefits, none align with Palo Alto's long-term commitment to zero emissions. Biodiesel still produces CO_2, CNG, and RNG, has methane leakage issues and requires infrastructure investment, and hydrogen remains too expensive and logistically complex to implement at scale.

Instead, our analysis will focus on the three remaining options: Diesel (as a baseline for comparison), Electricity, and Hydrogen (for future feasibility studies, despite its current limitations).

4. Total Cost Analysis over 20 years

Beyond environmental impact, cost feasibility remains central to Palo Alto's transition to a zero-emission fleet. A long-term cost analysis was conducted to compare the total ownership costs of different fuel alternatives over a 20-year period, considering variables such as vehicle replacement rates, annual cost of fuel and maintenance, cost of labor, and inflation. Before we dive deep into our analysis and our methods for doing things, here is a list of our constants, variables, and assumptions, most of which come from our point of contact at the City of Palo Alto, Phil Bobel, and nationally trusted sources of energy and price data:

Constants:

1. The City of Palo Alto has a fleet of 30 garbage/refuse trucks currently, of which 2 are electric, 25 are diesel, and 3 are biodiesel (10% of the entire fleet). Both diesel and biodiesel refuse trucks are interchangeable, meaning they can both use diesel/biodiesel interchangeably.
2. Each refuse truck is replaced after approximately 7 years due to their heavy use, and the unavoidable degradation in efficiency. This is regardless of whether they are electric trucks or diesel-powered.
3. One worker is assigned per truck, averaging 45 workers across shifts. Worker wage is $19 per hour (average from Ziprecruiter for California)
4. Trucks operate 1 day per week (54 days a year) and complete two daily routes on average. It is important to note that there is NO mid-route refueling: Trucks refuel only at designated docking stations at the end of the working day, and as a result, the infrastructure cost is mostly $0 for the City of Palo Alto. Since the docking station for all trucks is Santa Clara, we were told to assume that all trucks are fully fueled/charged at the start of the day, and their respective tanks/batteries can last the whole day. In our analysis, we based our calculations on the biggest tanks/batteries offered for each of these trucks since garbage trucks come with the option to customize fuel tank sizes and battery sizes. These numbers can be modified appropriately if specifics are known.
5. Inflation assumption: Fuel and acquisition costs increase at an average of 2.5% annually over a 20-year period. In our model, we randomised the inflation variable over the 20-year period, but it should be noted that they can be custom modified to change the calculation.

6. Only Diesel, Only Hydrogen, and Only Electric scenarios each start with 30 trucks of the respective type. Their respective costs would be $15 million, $21 million, and $24 million if all 30 trucks were acquired at the start of the model. Since that is unrealistic, we just calculate the cost/delta of replacing trucks throughout the 20 year span.
7. Truck replacement rate varies per scenario, with mixed-fleet scenarios incorporating both replacements and incremental additions. As informed by Phil, the City of Palo Alto replaces their trucks every 7 years, meaning with a fleet size of 30, that would mean an average 4 trucks a year. Since this is not always the case, our analysis made sure to replace anywhere from 1-7 trucks per year, making sure our fleet stayed most environmentally conscious, while also remaining realistic. More importantly, it must be noted that our analysis made sure that we can customize fleet proportions, and made sure to assume that in the cases that our fleet size is improper (i.e. not equal), we have ratios to make sure the model doesn't replace trucks every year. To simplify the point, suppose we have 20 diesel, 9 electric, and 1 hydrogen truck, our model makes sure to replace the hydrogen truck only once every seven years, even though an average of four trucks are being replaced yearly. Again, the numbers in this part of the model can be modified as needed.
8. A copy of our analysis can be found here:

   MS&E108: City of Palo Alto- Analysis Submission (or) using this link: https://docs.google.com/spreadsheets/d/1R7odMvqzWDU3FnjknYtGF3uDagdT4Yk3IhAdGj2_52o/edit?usp=sharing

Variables:

1. Fuel costs change depending on inflation

Assumptions:

1. Hydrogen, electric, and diesel trucks have different fuel efficiencies based on real-world studies.
2. All trucks are refueled at a central docking station at the end of each day. Docking Station is located in Santa Clara, and it is also the place all the garbage is taken to get sorted at the end of the day.
3. Hydrogen-powered trucks will rely on GreenWaste's existing supply chain to mitigate early-stage infrastructure costs.



Figure 5.A: Total Cost of Ownership - Model 1

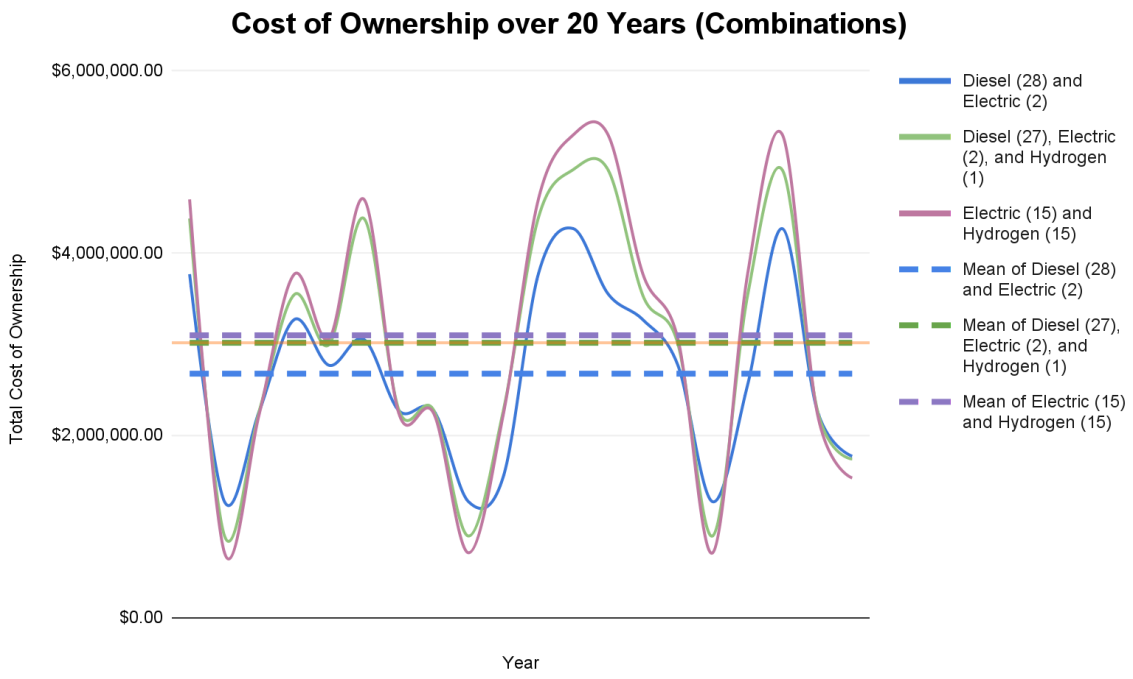


Figure 5.B: Total Cost of Ownership - Model 2

To assess the financial viability of alternative fuel options for Palo Alto's waste management fleet, a 20-year cost of ownership analysis was conducted. The evaluation considers critical variables such as truck acquisition costs, fuel prices, maintenance expenses, and truck replacement cycles.

The analysis explores two fleet transition strategies:

1. **Uniform fleet models**, where all 30 trucks operate using a single fuel type.
2. **Mixed-fleet models**, where different fuel types are used to evaluate phased transition strategies.

By breaking down these cost components, we gain insight into how different fuel options compare in both short-term affordability and long-term financial sustainability.

i. Uniform Fleet Cost Analysis

Figure 5.A, 'Cost of Ownership over 20 Years (Uniform),' examines cost trends for fleets exclusively powered by diesel, biodiesel, electricity, or hydrogen. This scenario assumes that each fleet starts with 30 trucks of the respective type, focusing solely on ownership and replacement costs over time. The key variable affecting cost are illustrated in Table 5.A:

	Truck Acquisition cost	Fuel prices per gallon,kWh, or pound	Cost per DEG	Maintainence cost
Diesel	$500,000.00	3.36	3.36	$6,000.00
Biodiesel	$500,000.00	3.96	$4.28	$6,000.00
Electric	$700,000.00	0.199	12.300752	$3,000.00
Hydrogen	$800,000.00	2	$11.00	$8,000.00

Table 5.A: Costs of Garbage trucks based on fuel types

Findings from the Uniform Fleet Chart:

Diesel and biodiesel fleets exhibit the most stable costs, with minor fluctuations due to inflation and periodic truck replacements. Electric fleets have a high upfront cost due to vehicle and charging infrastructure expenses but trend toward cost parity with diesel by Year 10-15 as fuel savings accumulate. Hydrogen exhibits the highest cost volatility, largely driven by high production and refueling expenses. Even with projected cost reductions, hydrogen remains significantly more expensive.

The mean cost lines provide a baseline comparison over time. Diesel and biodiesel have the lowest, confirming cost stability, while electricity is just a little higher. Hydrogen's mean cost remains the highest throughout the analysis.

This suggests that while diesel and biodiesel remain financially stable, they do not align with Palo Alto's long-term decarbonization goals. Hydrogen remains prohibitively expensive, whereas electric fleets present long-term savings potential but require significant upfront investment.

ii. Mixed-Fleet Cost Analysis

Figure 5.B, 'Cost of Ownership over 20 Years (Combinations),' explores hybrid fleet models that integrate different fuel types to assess whether a phased transition strategy could balance costs and sustainability. The scenarios analyzed include:

- Diesel-dominant fleets with partial electric integration (e.g., 28 diesel, 2 electric)
- Diesel-electric-hydrogen mixed fleets (e.g., 27 diesel, 2 electric, 1 hydrogen)
- Electric-hydrogen equal split fleets (e.g., 15 electric, 15 hydrogen)

Findings from the Mixed Fleet Chart:

Gradually integrating electric trucks into the existing diesel fleet offers a financially viable transition strategy, minimizing cost fluctuations. The Diesel (28) + Electric (2) fleet configuration shows the lowest cost variation, making it a stable and scalable option. Given that replacing a diesel truck with an electric one costs approximately $200,000 more per unit, a phased approach would allow the City of Palo Alto to make this transition without significant financial strain.

A critical consideration, however, is determining the tipping point at which electric adoption becomes too costly. As electric trucks gradually replace diesel trucks, the city's fleet composition will shift. Initially, the financial impact remains manageable, but once the fleet

reaches around 15 electric trucks, the annual replacement cycle—typically four trucks per year—could become significantly more expensive. At that stage, the city would not only be investing in new electric trucks but also replacing aging electric trucks from previous purchase cycles, compounding costs.

This raises an essential question for Phil Bobel and other city decision-makers: At what point does the financial burden of fleet electrification outweigh the benefits? A complete transition to electric may not be financially feasible, as the cumulative cost of replacements could become unsustainable. Identifying the optimal fleet balance—where cost savings from lower fuel and maintenance expenses justify the higher upfront costs—will be key in ensuring a cost-effective and sustainable fleet strategy for Palo Alto.

Adding hydrogen to the mix disproportionately increases costs, particularly in mixed fleets with a greater hydrogen proportion. The Diesel (27) + Electric (2) + Hydrogen (1) scenario has a higher total cost than a pure diesel-electric mix, largely due to hydrogen's expensive acquisition and fuel costs. However, it must be noted that hydrogen technology is very new, and thereby, expensive. We believe that in a couple years, the process of creating hydrogen fuel, and the cost of hydrogen-powered trucks will significantly decrease, and then Hydrogen powered garbage trucks would be perfect. As of present, the two biggest areas of concern are the higher acquisition cost (close to $100,000 more than electric) and the environmental cost of hydogen (i.e. gray hydrogen). Once green hydrogen is more readily available in the market, and hydrogen truck prices drop, we believe that it would be in the City's best interest to stop the implementation of electric powered garbage trucks into the fleet, and immediately being the integration of hydrogen, because on average, the CO2 emissions from the lifecylce of electricity is more than 10x that of green hydrogen (observable in Figrure 4.A).

Full electric-hydrogen fleets are the most expensive, with the Electric (15) + Hydrogen (15) scenario showing the highest cost fluctuations, reinforcing that hydrogen's current cost profile is prohibitive for short-term large-scale adoption.

Key Takeaways & Strategic Recommendations

These cost analyses highlight several important findings:

1. A fully hydrogen fleet is not financially viable at current cost levels, with prohibitively high acquisition and operating expenses.
2. Full electrification remains a long-term goal but presents high initial capital costs, requiring phased adoption for financial feasibility.
3. Diesel-electric hybrid models offer the best near-term solution, allowing Palo Alto to balance cost efficiency with emissions reductions.
4. Hydrogen should remain a future feasibility study, as cost reductions in fuel production and infrastructure are necessary before widespread adoption.

By leveraging a phased electrification strategy, Palo Alto can reduce emissions while maintaining financial stability. The next steps will be to refine the timeline and scaling strategy for transitioning to electric.

C. Environmental Impact Framework

1. Life Cycle Analysis

We have developed a life cycle analysis (LCA) table to help analyze the long term environmental impacts on the atmosphere that are derived from diesel, electric and hydrogen garbage trucks. It helps to determine greenhouse emissions that are released into the atmosphere. For the city of Palo Alto, they purchase new vehicles every 7 years. Garbage trucks that need to be cycled out are consequently donated to other cities. The life cycle analysis will help us determine the environmental footprint from each vehicle with its respective fuel type throughout its entire lifespan. This includes the production, manufacturing, and fuel consumption of a truck.

Fuel Type	CO2 Emissions (in metric tons)	Fuel Consumption (in metric tons)	Other Emissions (in metric tons)
Diesel	987	62	101
Hydrogen	~200	~150	~50
Green Hydrogen	~50	~40	~10
Electric	1262	1020	203

Table 4.A: Life Cycle Analysis of 4 Fuel Types

Based on the life cycle analysis above, we see the green hydrogen has the best total life cycle of CO2 emissions measuring at about 50 metric tons. In comparison to diesel, hydrogen, and electric, green hydrogen serves as a more sustainable fuel source for the City of Palo Alto. In addition, we see that electric vehicles produce the most CO2 emissions and consume the most fuel in its life cycle. If we compare electric and green hydrogen side by side, the consumption of

electric fuel is about 25 times more than green hydrogen. The other emissions factored into the LCA include methane, emissions, nitrous oxides, sulfur oxides, and more. Each fuel type produces a different quantity of these chemicals, but we will weight carbon emissions higher within the environmental impact framework as requested by the City of Palo Alto.

2. Sustainable Return on Investment

In order for our team to make a more holistic and accurate final recommendation, we decided to create a sustainable return on investment model (SROI). A sustainable return on investment model is a framework designed to measure the environmental value of a pilot or investment beyond the scope of revenue. Traditional finance metrics such as a return on investment (ROI) calculate the net return over the total investment. This metric is strong for calculating how profitable an investment is but does not consider the environmental or social impacts. Examples of overlooked factors include carbon emissions released into the atmosphere, community health, and job creation. By utilizing a sustainable return on investment model, we hope to take into account factors that are typically not quantified (i.e. environmental and health externalities). We hope that this model will allow us to create a final recommendation that is best for a sustainable future that evaluates long-term value and effect.

For the purpose of our model, we will be using the following formula:

$$\text{Sustainable Return on Investment (S-ROI)} = \frac{\text{Environmental + Health Impact}}{\text{Total Investment}}$$

Figure 5.A: Sustainable Return on Investment (SROI) Equation

Firstly, we will examine each component of this formula. For the environmental component, we will be examining CO2 emissions in metric tons per lifecycle. In the following figure, we derived CO2 emissions from the Life Cycle Analysis (Table 4.A). In other contexts, the environmental component can examine a reduction in water use, lower waste outputs, and prevention of land subsidence. However, we will examine CO2 emission because this was the primary focus area requested by the City of Palo Alto. For health benefits, we used the social cost of carbon determined by the Biden administration for each ton of CO2 produced ("Stanford explainer: Social cost of carbon"). We chose to focus on this because diesel has led to higher rates of asthma, which is something the city would like to reduce or prevent. Recall, from our decision analysis, the DM cares most about sustainability, which involves local air and community health. Finally, the total investment will be the cost of ownership calculated from the Comparative Cost Framework. Next, we will quantify the values of the equation. Please refer to the values below to see the comparisons across diesel, electric, and green hydrogen.

Fuel Type	CO2 Emissions (metric tons per lifecycle)	Health Impacts ($51 dollars per ton)	Total Investment (in Year 3)	S-ROI Calculated
Diesel	987	$50,337	$2,324,436.45	0.0221
Electric	1,262	$64,362	$2,413,395.94	0.0272
Hydrogen	50	$2,550	$2,996,501.46	0.0009

Table 5.A: SROI Calculations

Fuel Type	CO2 Emissions (metric tons per lifecycle)	Health Impacts ($51 dollars per ton)	Total Investment (in Year 3)	SROI Calculated

Diesel	2	2	1	4
Electric	3	3	2	3
Hydrogen	1	1	3	0.67

Table 5.C: SROI Calculations (RICE Framework)

It should be noted that in this model, a higher S-ROI number indicates there is a greater environmental harm. Furthermore, a lower S-ROI number results in a lower environmental harm. This can be explained upon looking at the factors. A greater CO2 emission is worse for the environment as it contributes at higher rates to the greenhouse effect and climate change overall. With health impacts, a higher social cost on health (in regards to emissions) leads to increased pollution-related health issues, reduced quality of life, and worse air quality. Finally, a larger total investment means a greater investment, which can result in budget constraints and a reduction of allocations to other important city operations. All of this combined reveals why the goal of this model is to have a lower final S-ROI.

3. Evaluation of Goals and Measurements

C. Regulatory and Political

As discussed in the literature review, the California Air Resources Board (CARB) in January 2025 withdrew its request for a waiver to enforce the federal Advanced Clean Fleets (ACF) regulations; this was due to projected roadblocks under the current federal administration. Starting from this point, we will analyze the federal outlook with regards to hydrogen and EVs and look at a few signals under the Trump administration so far. Then, we understand the current regulatory and financial environments and discuss how they may evolve over the next 4 years.

From there, we will project a few plausible scenarios and their potential impact on hydrogen fleets in Palo Alto.

In January 2025, President Trump moved swiftly to roll back many of his predecessor's clean vehicle initiatives. On his first day back in office, he signed an executive order ("Unleashing American Energy") that revoked President Biden's non-binding goal for 50% EV sales by 2030 and halted distribution of certain clean transportation funds. This order froze federal grants and loans for electric vehicle (EV) infrastructure – for instance, pausing the unspent $5 billion for EV charging stations. The administration framed EV incentives as "unfair subsidies" and indicated it would consider ending EV and fuel cell vehicle tax credits to eliminate policies that "favor EVs over other technologies." In line with this, President Trump also ordered a review of California's waiver that allowed a 2035 gasoline vehicle sales ban, aiming to invalidate state zero-emission mandates. These actions signaled a clear federal pullback from aggressive electrification mandates.

The Trump administration's broad freeze extended beyond EVs to clean energy programs at large. In late January, the Office of Management and Budget (OMB) directed agencies to "immediately pause" disbursement of funds from the 2021 Infrastructure Investment and Jobs Act (IIJA) and 2022 Inflation Reduction Act (IRA). This included halting new spending on flagship initiatives like the Department of Energy's regional hydrogen hubs (a combined $7 billion program) pending further "review." Crucially, multiple lawsuits were filed within days. Two federal courts issued temporary restraining orders, forcing OMB to rescind its freeze memo and blocking implementation of the funding pause. As a result, agencies like DOE have been prohibited from freezing or canceling existing awards on the basis of Trump's order. However, officials retain discretion in how fast to roll out funds, meaning delays and uncertainty remain.

Hydrogen industry observers note that many projects essentially went on hold until it was clarified that the freeze wouldn't apply. In short, Trump's attempts to rescind federal hydrogen and EV funding have been partly checked by the courts, but agency appointees can still reassess programs.

While the administration broadly casts doubt on government support for electrification, hydrogen has received mixed signals. Trump campaigned on rolling back subsidies for "the mass production of hydrogen" alongside other clean energy like wind and solar, suggesting a potential scaling back of federal hydrogen R&D and deployment funds. Indeed, the funding freeze explicitly targeted hydrogen programs (e.g., the H2 hubs). At the same time, some stakeholders see an opening for hydrogen under Trump's "all-of-the-above" energy approach. The DOE's clean hydrogen production tax credit (45V), which offers up to $3/kg for low-carbon hydrogen, remains in effect as it was created by statute. Final Treasury rules for the 45V credit were released in early 2025, giving developers much-needed clarity to move forward. Lawyers have noted that tax credits like 45V are not directly affected by the funding freeze, providing a degree of stability for hydrogen investors. In addition, Trump's pro-fossil rhetoric may favor "blue" hydrogen (from natural gas + CCS). Industry voices, such as the CEO of Plug Power, argue that deregulatory, pro-business policies could actually benefit hydrogen, since Trump's "energy dominance" agenda includes expanding both green and blue hydrogen as fuel options. Notably, over 100 energy and industry groups (including the American Petroleum Institute and hydrogen hub developers) have petitioned Congress and the administration to preserve the hydrogen production credit, touting hydrogen's role in energy abundance and job creation. In summary, at the federal level new hydrogen initiatives face headwinds, but existing incentives (tax credits) and programs with bipartisan support may endure despite the administration's opposition.

Despite some anti-hydrogen signals on a federal level, on a state level, support for hydrogen remains strong in California. Despite the CARB withdrawal of a federal waiver to enforce the Advanced Clean Fleets regulations, the state and local government fleet requirements remain in force, as those do not require EPA approval. In other words, cities and public agencies are still bound by ACF's ZEV purchase rules, whereas private trucking companies have a temporary reprieve. This means that cities like Palo Alto must still ensure (as of January 2024) that half of new fleet trucks are ZEVs (battery-electric or hydrogen fuel cell), and in just two years all new truck purchases must be ZEVs. This effectively means any new garbage truck ordered in 2027 or later cannot be diesel or natural gas – it must be hydrogen, battery-electric, or another zero-emission technology. Additionally, ACF includes a provision that no new internal combustion engine vehicles (model year 2024 or later) can be added to a public fleet unless they meet the latest California engine standards– ensuring any interim diesel purchases are as clean as possible. These rules are in force for Palo Alto (they were not affected by CARB's waiver withdrawal), so the city has a legal mandate to begin greening its fleet now. By opting for hydrogen trucks to satisfy the 50% requirement today, Palo Alto can gain operational experience before the 100% ZEV purchase requirement hits. Not complying (i.e. buying new diesel trucks beyond allowed percentages) is not really an option, as the state can levy penalties and, more practically, such trucks might not even be registrable in California after 2030. The regulation is expected to remain strict or even tighten – if anything, a future pro-climate federal administration might enable California to enforce even broader fleet rules (covering private fleets as well), but the public fleet portion is essentially set and unlikely to be relaxed. In addition, the California Energy Commission (CEC) approved a $1.4 billion investment plan in December 2024 to expand ZEV infrastructure, including both EV charging and hydrogen fueling stations, which is rolling

out in 2025. This record funding will build upon California's existing network of 50+ retail hydrogen stations and thousands of chargers, extending it with more stations to support the growing fuel cell vehicle fleet (light-duty and potentially medium/heavy-duty).

In the heavy-duty sector specifically, California's HVIP (Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project) remains a key program. HVIP offers point-of-sale vouchers to offset the cost of zero-emission trucks – including battery-electric and hydrogen fuel cell trucks – often reducing upfront costs by hundreds of thousands of dollars. For example, fuel cell Class 8 trucks (like the Nikola Tre FCEV) qualify for base vouchers around $240,000 per truck, with potential add-ons (e.g. an extra $30k for drayage use). However, HVIP funding is finite and in high demand. CARB's budget for clean vehicle incentives was sharply reduced for FY 2024-25 (only $35 million for all clean transportation incentives, a steep drop), reflecting state budget constraints. Furthermore, program rules have changed: as of January 1, 2025, large fleets (50 or more trucks) are no longer eligible for HVIP vouchers. This policy shift aims to direct funds to smaller fleets and ensure big companies comply via regulations rather than subsidies. A city like Palo Alto, with a relatively small municipal fleet, can still tap HVIP for its zero-emission truck purchases. Other California funding streams include the Low Carbon Fuel Standard (LCFS) credits, which provide ongoing incentives for using low-carbon hydrogen fuel – the LCFS market can yield roughly $3–$6 per kg of hydrogen in credits, helping to offset operating costs for hydrogen trucks. The state is also continuing grants for hydrogen station development (CEC's Clean Transportation Program has offered grants up to $3–$5 million per new station to private developers, and is funding heavy-duty hydrogen fueling demonstrations, especially at ports and freight corridors). In sum, California in 2025 is actively reinforcing its

ZEV programs to ensure that the momentum for electric and hydrogen vehicles isn't lost, even as federal support wavers.

Now, let us consider three possible scenarios and what they might mean for the viability of hydrogen-powered waste trucks for Palo Alto over the next four years:

Scenario 1: "Federal Dismantling, State Stalemate" (Worst Case for Hydrogen)

Policy Environment: In this scenario, the Trump administration succeeds in substantially dismantling federal support for zero-emission vehicles. By 2026, Congress passes a tax reform (or as part of budget deals) that eliminates the Commercial Clean Vehicle federal tax credit and perhaps even the hydrogen production credit. President Trump's orders lead to ongoing litigation, but ultimately many IRA programs are frozen or rescinded. The $7,500/$40,000 EV/FCEV purchase credit is repealed (as promised in Trump's campaign), removing a significant federal subsidy for clean trucks. The DOE's hydrogen hub funding remains stalled; new hydrogen infrastructure grants from USDOT/EPA dry up. The EPA also weakens emissions standards and prevents states from adopting new ZEV mandates (California's waiver for future rules is denied), thereby slowing the national push toward hydrogen and EV fleets. California continues enforcing ACF for public fleets but cannot extend mandates to private fleets due to federal preemption. State incentive funds (HVIP, etc.) become oversubscribed and are not significantly replenished given economic constraints. By 2027, HVIP vouchers for heavy trucks are phased out as funds are exhausted. California's own ZEV rebate (if introduced) is geared to consumers and provides little help for heavy-duty fleet costs. In short, state support exists but is limited, and federal support is largely absent.

Financial Impact: Under this worst-case, the economics of hydrogen trucks weaken. With no federal tax credit, Palo Alto loses up to $40k per truck in savings. Hydrogen fuel might also

be more expensive – if the 45V hydrogen production credit were repealed or undermined, green hydrogen producers would struggle, keeping fuel prices high. Infrastructure deployment could stall without federal grants, meaning fewer hydrogen stations. California's LCFS credits would still encourage some fuel production, but overall, hydrogen truck acquisition and operating costs in this scenario could be significantly higher than battery-electric alternatives.

Regulatory Impact: Even in this scenario, Palo Alto must comply with California's fleet ZEV mandate – that doesn't go away. By 2027 the city cannot buy diesel trucks. So the choice is between battery-electric and hydrogen fuel cell trucks. With less external funding for hydrogen, the city might lean toward battery-electric options which have had more market development (thanks to consumer EV momentum) and more charging infrastructure funding (California's investment in charging, for instance, continues).

Palo Alto's Decision: Without federal incentives, Palo Alto may still pilot only one or two hydrogen trucks but avoid full fleet conversion due to high costs. Unless hydrogen's operational benefits justify the premium, the city would prioritize battery-electric trucks to comply with state ZEV laws. Hydrogen adoption may shift to a "wait and see" approach, with the city maintaining readiness but not committing heavily until the policy climate improves.

Scenario 2: "Minimal Federal Support, Strong State Leadership" (Moderate Case)

Policy Environment: In this scenario, much of what we see in early 2025 continues: the Trump administration's efforts to curb climate programs face legal and political resistance, but no federal support emerges either. The IRA's key provisions (like the vehicle and hydrogen tax credits) remain on the books through 2030. However, federal agencies under Trump significantly slow-roll new grants and emphasize fossil-fuel-friendly interpretations. No new federal EV or Hydrogen initiatives are launched, but also the administration doesn't outright kill existing

credits. Essentially, federal support stagnates but doesn't completely vanish. California compensates for federal inaction, enforcing ACF for public fleets and exploring legal workarounds to push private fleets toward ZEV adoption. Interstate collaborations may also arise (e.g. a West Coast hydrogen fueling corridor) to pool resources.

Financial Impact: In this status quo, most current incentives remain available in the near term. Palo Alto retains the $40k federal credit per truck, California's HVIP (though funding may dwindle), and low-cost hydrogen through 45V and LCFS credits. While federal grants slow, state programs may fund local Hydrogen stations. Hydrogen fuel costs should steadily decline as projects that were already planned move ahead (perhaps on a slower timeline). Hydrogen fuel prices decrease as DOE-funded projects progress, but hydrogen trucks still rely on incentives to remain competitive with electric.

Regulatory Impact: California's mandates remain the driving force, meaning that Palo Alto must still procure ZEV trucks under ACF. The federal government neither helps nor blocks state mandates, allowing California to set strict fleet policies, but enforcement is still blocked for private fleets. For the most part, state and local regulations govern the day-to-day decisions.

Palo Alto's Decision: In this scenario, hydrogen waste trucks remain a viable option for Palo Alto, though one of two possible paths (the other being battery-electric). The policy landscape provides some support in which the city can stack federal and state incentives to cover a substantial portion of the truck and infrastructure costs. For instance, a hydrogen garbage truck in 2025-2026 might get $240k from HVIP + $40k federal credit + additional LCFS fuel credits annually – making its lifecycle cost much closer to parity with a diesel truck. Palo Alto would also consider operational factors: hydrogen trucks could offer quicker refueling and possibly longer range, which are valuable for heavy refuse routes. The steady incentive environment

means the city could reasonably pilot and deploy hydrogen trucks with manageable financial risk. However, regional fueling coordination is key since the city may have to invest in shared stations across the state rather than relying on federal support, which could drive costs up. In this scenario, hydrogen is a practical option alongside battery-electric vehicles, ensuring compliance while hedging against future regulatory shifts.

Scenario 3: "Hydrogen-Friendly" (Best Case for Hydrogen)

Policy Environment: The federal stance evolves into an "all-of-the-above" energy strategy that explicitly favors hydrogen as an alternative to battery electrification. Facing pressure from industry and wanting to reduce reliance on purely battery EVs (with narratives about supply chains, etc.), the Trump administration and Congress pivot to support certain hydrogen initiatives even as they cut back on EV-centric programs. Importantly, in this scenario the hydrogen production tax credit (45V) is retained and possibly made more flexible – for instance, the administration might relax rules to make it easier for natural gas-based hydrogen to qualify (which aligns with fossil fuel interests). California, while still favoring all ZEVs, is happy to take any federal support for hydrogen and runs pilot projects funded by a mix of state and federal dollars).

Financial Impact: Incentives for hydrogen infrastructure and vehicle deployment increase, with possible new tax credits for fueling stations. EPA's clean truck grant program could be rebranded to include hydrogen, expanding federal funding. Private investment would also grow – oil & gas companies might partner with truck OEMs to subsidize hydrogen truck deployment as a way to create demand for their hydrogen fuel. By 2030, one could envision lower hydrogen fuel costs than in other scenarios because both federal incentives (45V and others) and increased volume drive the price down. Also, if hydrogen stations get federal

funding, Palo Alto could see a hydrogen fueling site built in the Bay Area with national dollars, reducing the infrastructure burden on the city.

Regulatory Impact: Hydrogen gains bipartisan support, allowing CARB's ZEV sales mandates for trucks to move forward without federal interference. No regulatory barriers hinder hydrogen, making it a fully recognized alternative to battery-electric fleets.

Palo Alto's Decision: In a scenario where hydrogen enjoys bipartisan or at least broad support, Palo Alto's choice to adopt hydrogen waste trucks becomes highly attractive. The city could receive substantial external funding, and with lower fuel costs and more certainty of infrastructure, hydrogen trucks' operational advantages (long range, fast fueling, heavy payload capability) shine, making them perhaps more practical than battery trucks for heavy stop-and-go refuse service. Palo Alto would likely move forward confidently with hydrogen in this case, potentially converting its entire waste fleet by 2030 to fuel cell trucks. The risk of being left with unsupported tech is low, since both federal and state entities are promoting hydrogen usage. In fact, not pursuing hydrogen could mean missing out on generous funds or partnership opportunities. Therefore, under this hydrogen-friendly scenario, investing in hydrogen waste trucks makes strong strategic sense for Palo Alto.

Overall, Palo Alto's exploration of hydrogen-powered waste trucks must account for a fluid policy landscape. The analysis above illustrates that in most foreseeable scenarios, the regulatory mandate for zero-emission fleets in California remains in place or strengthens, meaning the city must transition away from diesel regardless. The financial and policy support for how to do so can swing widely. In a deeply unfavorable scenario (Scenario 1), hydrogen trucks face higher hurdles, and the city might pivot to other solutions unless it can find creative funding. In the moderate and favorable scenarios (Scenarios 2–3), multiple incentives and

mandates align to make hydrogen trucks not only viable but attractive for achieving climate and air quality goals. As of early 2025, Palo Alto has a window to capitalize on existing funding and de-risk an initial deployment. With state laws mandating ZEV fleet adoption, moving now allows the city to secure incentives while gaining operational experience. Looking ahead, Palo Alto should maintain flexibility: if hydrogen funding declines, battery-electric trucks may become the default, but if hydrogen infrastructure and policy support expand, the city will be well-positioned to scale up. Investing in a pilot program now while still also monitoring policy shifts would ensure that Palo Alto can comply with state mandates while maximizing financial and operational benefits.

D. Aggregate Analysis of Cost, Environment, and Regulation

As a result, our team has made the decision to provide a **Scenario Matrix** that will be weighted in a score of four. The representations of the pie charts will point to the MoSCoW method learned in *MS&E 165: Introduction to Product Management.* The MoSCoW prioritization framework categories each feature (in this case truck) into must-have, should-have, could-have, and won't have. It will assess the investment score based on the combination of trucks. Note that the constant number of garbage trucks in the City of Palo Alto's fleet remains 30. Thus, the number represented in parentheses by each fuel time in **Table 6.B.** represents the truck quantity in the hypothetical scenario. In order to aggregate the analysis in this project, we will draw together the Decision Quality Framework, Comparative Cost Framework, and Environmental Impact Framework to outline the following:

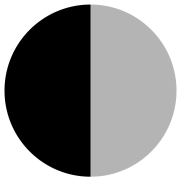
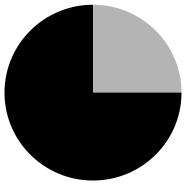
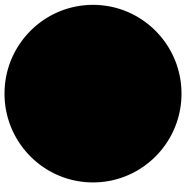
Category	Cost of Ownership	Social Cost of Carbon (SCC)	Regulatory Risk	Recommendation (MoSCoW)
	Low Cost	Low Cost	Low Risk	Must Invest
	Medium Cost	Medium Cost	Medium Risk	Should Invest
	High Cost	High Cost	High Risk	Could Invest
	Extreme Cost	Extreme Cost	Extreme Risk	Won't Invest

Table 6.A: Applying the MoSCoW Framework for the 20-Year Scenario Analysis

20-Year Scenario Analysis					
Truck Combination	**Cost of Ownership**	**Social Cost of Carbon**	**Regulatory Risk**	**Sum**	**Recommendation (MoSCoW)**
Diesel (30)				0.67	Won't Invest
Electric (30)				0.67	Won't Invest
Hydrogen (30)				0.5	Should Invest
Diesel (28) and Electric (2)				0.58	Could Invest
Diesel (27), Electric (2), and Hydrogen (1)				0.67	Won't Invest
Electric (15) and Hydrogen (15)				0.58	Could Invest

Table 6.B: Recommendation for 20-Year Scenario Analysis

V. Conclusion & Recommendations

Ultimately, rather than investing in hybrid trucks with multiple fuel sources, Palo Alto should adopt a hydrogen fleet, where service collection is performed by a gradual pilot of hydrogen-powered garbage trucks. This strategy distributes maintenance complexity, reduces investment costs, and ensures a steady transition toward a fully zero-emission fleet by 2035. In order to ensure that our DM can take our analysis forward, we have researched proximal and credible hydrogen suppliers and electric suppliers.

Hydrogen Suppliers:

1. Air Products - Allentown, Pennsylvania
2. Clean Energy Fuels - Newport Beach, California
3. Zero Emission Industries (ZEI) - Alameda, California
4. Bloom Energy - San Jose, California
5. Fuel Cell Energy - Danbury, Connecticut
6. Pearson Fuels - San Diego, California

The final recommendations for the City of Palo Alto can be summarized below:

(1) Gradually invest in more hydrogen trucks to align with long-term sustainability goals and evolving regulations. This ensures a scalable transition while mitigating financial and operational risks.

(2) Cease further investments in diesel trucks due to their declining cost-effectiveness, increasing regulatory restrictions, and long-term environmental impact.

(3) Leverage policy incentives and emerging technologies to optimize the cost-benefit ratio and ensure a smooth transition.

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