Transforming Warehouses Towards a Sustainable Future

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ABSTRACT

Climate change is a global problem, and CO_2 emissions are the primary cause of rising temperatures. Many companies, including our capstone sponsor Maersk, have committed to reaching net zero emissions by setting decarbonization targets. In this project, our goal was to identify specific actions that could be taken at the warehouse level to reduce greenhouse gas emissions and help companies achieve their decarbonization goals. Our approach involved identifying sources of emissions, shortlisting technologies that could be adapted based on their applicability to the operations of Maersk warehousing and distribution subsidiary companies in the United States and developing a methodology to evaluate each solution's key performance indicators: payback and environmental impact. The result was a set of recommendations prioritizing each solution's implementation and scaling to other facilities. Our analysis revealed that some solutions, such as solar energy, could reduce Scope 2 carbon emissions by 100% due to eliminating supply of electricity from the grid while also decreasing electricity costs by 39%. Finally, to evaluate the different sustainable solutions in an integrated way, we developed a framework that identifies the key factors and patterns affecting the attractiveness and further implementation of each solution. Our findings suggest that combining initiatives such as the electrification of moving assets with renewable-energy generation systems can significantly improve the payback period further, reducing it by almost 9%.

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1. INTRODUCTION

1.1. Motivation

With the accelerated rates of average global temperature increase, the problem of climate change is slowly getting the needed global attention to focus efforts on limiting CO_2 emissions, which are the primary cause of global warming. The average global surface temperature in 2021 was recorded as being 1.51 °F (0.84 °C) warmer than the twentieth-century average temperature (13.9 °C) and 1.87 ˚F (1.04 ˚C) warmer than the pre-industrial period (1880-1900), making it the sixth warmest year on record (Lindsey & Dahlman, 2021). Even though such an increase may not appear high, from 2009 to 2015, the cost of damage caused by weather and climate disasters in the U.S. is estimated to be 1.16 trillion USD (National Atmospheric and Oceanic Administration, 2022); a number that could climb up to 2 trillion USD per year by 2030 (Gardner, 2022). In this context, the question of sustainable development becomes critical to reduce the impact on our environment. Human activity generates annual greenhouse gas (GHG) emissions of around 50,000 megatonnes CO2e, of which approximately 5.5% is contributed by the logistics and transport sector (Doherty & Hoyle, 2009). In this vein, the largest players in various industries, including logistics companies, understand the importance of their role in reducing the environmental impact of their operations by focusing on sustainable development. Moreover, pressure from both regulatory agencies and customers also promotes green organizational responses and enhances green innovation performance (Huang et al., 2016). For example, for the fashion industry, there has been a clear customer shift to sustainable behavior: 66% of all respondents, and 75% of millennial respondents, said they consider sustainability when making a purchase (Amed et al., 2020).

Our project sponsor, Maersk, one of the global leaders in transportation and supply chain solutions, has set its decarbonization target to reach net zero emissions across all businesses by 2040. Moreover, the organization aims to provide 90% green contract logistics operations across scope 1 and 2 emissions by 2030 (A.P. Moller - Maersk, 2021b). Its presence in 130 countries all over the world with more than 3 million square meters of warehousing capacity worldwide makes Maersk a key player in the global shipping market. As for warehouse complexes, Maersk clearly characterizes them as an integral part of a strong supply chain, focusing on a significant number of initiatives to modernize the relevant infrastructure from automation and robotization of processes to continuous training of its workforce (A.P. Moller - Maersk, 2022).

As GHG emissions caused by warehousing are estimated to be 25% of the ones caused by transportation (Rüdiger et al., 2016), Maersk is setting up a roadmap to the decarbonization of their warehouses in line with the organization's vision of sustainability. The Maersk's organization's warehousing and distribution subsidiary companies in the United States are currently working diligently to to bring new warehouse complexes to sustainability. However, the challenge persists of reducing the carbon emissions of existing warehouses built before 2010, which represent 75% in total number of warehouses in North America.

1.2. Problem Statement and Research Questions

Considering the scale of Maersk's geographic presence and the high percentage of existing warehouses that would benefit from a systematic reorganization to bring them to sustainability -- 549 warehouses worldwide with 75% of them approximately requiring retrofitting (A.P. Moller - Maersk, 2021a) - the organization's key challenge lies in identifying and implementing scalable improvements while taking into account costs and payback limitations.

From 2022 onwards, new warehouses will be designed and built to operate with minimum environmental impact aspiring to have a minimum certification level of LEED 'Platinum' (Leadership in Energy and Environmental Design, https://www.usgbc.org/leed), BREEAM 'Excellent' (Building Research Establishment Environmental Assessment Method, https://bregroup.com/) or equivalent accreditation. Meanwhile, the organization sees the importance of launching a global retrofitting program for Maersk's existing warehouses to be able to achieve their targets of carbon footprint reduction by 2030 and 2040.

There are two main types of warehouses within Maersk's business model, fulfillment and transload, which differ in their layout, processes, and objectives. Therefore, each warehouse type will need to be studied separately.

Warehouses' GHG emission reduction initiatives are many. However, in the absence of a structured approach to identifying and prioritizing areas for improvement in a specific warehouse, there is a risk of focusing efforts on and investing in less impactful initiatives, which can delay the transition to the desired sustainability targets of the sponsoring organization.

In this context, our capstone project will aim to answer the following questions:

- Which GHG reduction action can be considered in each warehouse type?

- Which criteria and assessment methodology should be used to rank available solutions in terms of payback, environmental impact, and scalability?
- How can the organization implement selected opportunities in the fastest and most efficient way?

The scope of the project will be limited to 2 types of warehouses, located in North America: fulfillment and transload. For each warehouse type, a specific facility to be proposed by Maersk as an object of this study. The project will cover sources of emissions and solutions to offset them located inside of facilities.

1.3. Project Goals and Expected Outcomes

The project's overall goal is to provide Maersk with an efficient, scalable, and standardized method of identification and assessment, as well as implementation guidelines for sustainable opportunities for each type of their warehouses network in North America. This method should additionally provide a clear guideline to implement such opportunities.

We hypothesize that this methodology will help Maersk to identify the right and key GHG reduction initiatives. Moreover, it will help the organization to prioritize which initiatives should be implemented first. In order to identify the comprehensive list of GHG reduction opportunities and develop an importance grading methodology, scientific sources, public reports and information about warehousing market players will be studied with the goal to identify the industry's best practices and rank them considering their relevant costs and environmental impact.

The deliverables of the project shall include:

1. An identification and assessment of potential sustainable solutions at the warehouse level.
2. Prioritization of solutions based on payback and environmental impact parameters.
3. A guideline for the implementation of the identified solutions at each warehouse level.
4. A framework that integrates the evaluation of sustainable solutions in warehouses.

Once abovementioned approach is in place, the organization is expected to have a clear guideline for sustainability opportunities identification for both warehouse types: fulfillment and transload. Doing so will help the organization properly identify opportunities for sustainability and assess their performance. Further ranking of mentioned solutions and guideline for their implementation will contribute to achievement of Maersk's sustainability goals. The final outcome, the framework, will also help other companies and industries to evaluate sustainable solutions in a warehouse, identifying the key factors and patterns that affect the appeal and further implementation of each solution.

2. STATE OF THE ART

To address the central problem of our capstone project -- how to bring the existing warehouses to a sustainable level -- we reviewed the available sources of information in several areas: (1) definition of a sustainable warehouse, (2) Greenhouse Gases (GHG) estimation methods, and (3) available solutions to decrease or offset GHG emissions.

2.1. Definition of a Sustainable Warehouse

Defining a sustainable warehouse starts with an understanding of what sustainability is. As per the United Nations, sustainability is “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 2019). The term sustainability is also directly linked to the definition of sustainable development, which is based on three pillars: economic, social, and environmental (United Nations, 2020).

These pillars of sustainability can be also found in a definition of a green building, the key concept in terms of defining what a sustainable warehouse is. The US Green Building Council defines a green building as “an effort to amplify the positive and mitigate the negative of environmental effects throughout the entire life cycle of a building” (Kriss, 2014). This definition also is in line with the ones provided by scientific sources. For example, Rutgers University defines a green building movement as “an attempt to minimize and eliminate negative impacts and maximize environmental, economic and community/human benefits” (Rutgers University Center for Green Building, 2022). This view is also supported by Tan: “a sustainable warehousing company would not only have to consider the economic factors, such as rent and operations costs, but also balance the social and environmental effects that occur within the warehouse compound as well as its surrounding vicinity" (Tan et al., 2009).

Similarly, other sources also define a green building/warehouse and a sustainable warehouse by highlighting the importance of meeting environmental, social and governance (ESG) criteria (Ranpak, 2022). At the same time, sources emphasize the blurred borders between sustainable warehouse and a green building/warehouse. Although Malinowska highlights that the key difference of a sustainable warehouse lies within the focus on internal warehousing operations (Malinowska et al., 2018). Considering scientific sources, we can define a sustainable warehouse as a green building focusing on minimizing the negative economic, social, and environmental impacts throughout its lifecycle and internal operations.

Furthermore, to gain an understanding of the current business definition of a sustainable warehouse, the project research considered reviewing the sustainability reports of major players in the logistics industry where warehousing is considered as one of their key functions. Unfortunately, none of the biggest industry players has a clear definition of a sustainable warehouse. However, their understanding of sustainability can be interpreted by the type of energy-saving initiatives that were rolled out across their warehousing system. For example, Agility promotes sustainability by transitioning their warehouses into an automated, lean, and green building (Agility, 2021). Cyzerg focuses on reducing energy and water consumptions while decreasing dependency on traditional energy sources with high GHG emissions (Sunol, 2021). As for DHL, the company prioritizes initiatives connected to the implementation of solar batteries (DHL, 2019). Amazon, on the other hand, has a more diverse view in this avenue. Starting with low-carbon concrete technology for new facilities, Amazon carries out their efforts with water management improvement and solar panel deployment after the warehouse construction completion (Amazon, 2021). UPS focuses on renewable energy as well as automatization and efficiency improvement (The Foundation For Future Supply Chain, 2022). XPO also focuses on energy use optimization and additional initiatives, such as recycling (XPO Logistics, 2017).

Considering the uncertainty of the industry's definition of a sustainable warehouse, a solution may reside in following recognized sustainability standards. Among such standards, the following can be identified: LEED, ICC 700, Green Globes, and BREEM. LEED, being the world's most widely used green building system (U.S. Green Building Council, 2022), is also accepted by Maersk as a key guideline to define what a sustainable building is. LEED considers 4 levels of certification depending on the results of a point-based grading system: platinum, gold, silver and certified (U.S. Green Building Council, 2022a). This approach clearly allows differentiation of facilities based on the level of implemented sustainability practices. However, regardless of the awarded certification level, LEED considers all certified facilities sustainable ones. LEED standard evaluates a building with a rounded 360 approach rather than simply focusing on one isolated element such as energy, water, or health. This can be seen via LEED's checklist that focuses on point accumulation in multiple different areas to reach one of 4 levels of certification mentioned above. The checklist covers the following zones: (1) Location and transportation, (2) Sustainable sites, (3) Water efficiency, (4) Energy and atmosphere, (5) Materials and resources, (6) Indoor environmental quality, (7) Innovation, (8) Regional Priority. Consideration of the mentioned improvement zones provides a clear guideline in terms of a proper focus to reach a sustainable level of a specific facility. As the scope in LEED is very large, we agreed with our sponsoring organization to focus on two sections where the available solutions in the market to retrofitting existing warehouses have the highest impact on LEED scoring system: water efficiency and energy & atmosphere.

2.2. Greenhouse Gases (GHG) Estimation Methods

It is important to evaluate the current GHG budget of a specific facility or a company to be able to estimate the impact of perspective sustainable initiatives. For that reason, several applicable standards have been implemented: World Resource Institute (WRI), GHG Protocol, ENCORD's Construction CO2e Measurement Protocol, Set of BS Standards of UK, and EU origin, Group of PAS Standards (IEMA, 2017). GHG protocol is acknowledged as the most representative among them. Thus, more than 9 out of 10 Fortune Top 500 companies responding to CDP used GHG protocol to roll out sustainable initiatives (Greenhouse Gas Protocol, 2022).

GHG protocol was developed together by the World Resource Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) in 2001. The purpose was to set up an internationally acknowledged set of standards to account and report GHG. The document covers 11 chapters starting from overview of primary GHG accounting and reporting principles finishing with setting GHG targets. Chapter 6 specifically covers the approach to calculating GHG emissions. For GHG emissions calculation, all the emissions sources must be divided into 3 groups: Scope 1, Scope 2, and Scope 3. Scope 1 are direct emissions from sources controlled or owned by the organization. Scope 2 emissions come from generation of purchased electricity. The rest of emissions refer to Scope 3.

GHG emissions from scope 1 must be assessed using the quantities of purchased commercial fuels and emission factors published by the U.S. Environmental Protection Agency (EPA). Scope 2 emissions must be calculated from recorded electricity consumption and electricity supplier-specific local grid or other published emission factor. Scope 3 GHG emissions will primarily be calculated from activity data such as fuel use or passenger miles and published or third-party emission factors. To ease the GHG emissions calculations, GHG protocol implemented the set of templates to assess emissions for all 3 scopes. The mentioned templates will be used in this project to calculate GHG emissions.

2.3. Available Solutions to Decrease or Offset GHG Emissions

With the accelerated increase in awareness of the importance of reducing the CO_2 emissions generated by businesses, solutions to reduce GHG emissions are getting the needed R&D budgets to become more advanced and effective. Besides the standard clean energy generation solutions on site, we see a technological race between companies to offer technologies that would reduce the energy consumption in a warehouse, targeting the areas with high energy consumption. In our project, we segment the available solutions based on the main areas of energy and water consumption within a warehouse:

- Heating, Ventilation, And Air Conditioning (HVAC):

Being the highest contributor to the energy consumption level in a warehouse (Ries et al., 2016), HVAC systems get significant attention from companies aiming to reduce the energy consumption of their warehouses. Some of the available solutions in this area are:

- Smart Windows: Windows can considerably contribute to the heat generation or heat loss in a building depending on the time of the year. In summer, windows transmit more than 70% of the heat in a building, while in winter they are responsible for 30% of the heat loss (Zhou et al., 2021). Smart windows are able to automatically adjust the energy transmitted levels depending on the external environmental conditions (Casini, 2015). Using smart windows can generate an energy saving up to 20% in the heating and cooling consumption, along with an additional 20% from the lighting energy consumption (Morecroft, 2022).
- High Volume Low Speed (HVLS) Fans: characterized by their having a diameter greater than 7 ft (Department of Energy, 2014), HVLS fans can introduce a notable 15% reduction in energy costs when installed in a building (Mohamed et al., 2021). With a required capex of 5 to 10 thousand UDS per fan, this solution tends to be popular not only in warehouses but also in other public places with open spaces such as schools and malls (Chang & Ng, 2021).
- Smart Thermostat: with a negligible price and installation costs, those programmable smart devices can reduce energy consumption from 1 to 2% (Patterson et al., 2022).
- Loading docks seals: These seals offer a mechanism to close the gaps between the openings of the loading docks in a warehouse and the back of tuck arriving to offload. They are especially effective in refrigerated

warehouses in areas with a hot climate and can increase the energy efficiency next to the loading dock by 90% (Parts Brite, 2018).

- Infrared heaters: The generated efficiency from using infrared heaters highly depends on the layout of the warehouse. They are most effective in warehouses with large areas and high ceilings and can drive down energy consumption in winter by 23% (Chen & Energy, 2007). Other sources suggest a high saving of 40% compared to the conventional air heaters (Roberts Gordon, 2022).
- White roofs: White roofs are best used in warehouses located in areas with a hot climate. Thanks to the reflective white material coating the roof surface, the roof will reflect 80% of the sunlight. On a typical summer afternoon, a white roof will be 31°C (55°F) cooler than a gray roof (Energy Star, 2022). “Substituting a weathered cool white roof (solar reflectance 0.55) for a weathered conventional gray roof (solar reflectance 0.20) yielded annually a cooling energy saving per unit conditioned roof area ranging from 3.30 kWh/m^2 in Alaska to 7.69 kWh/m^2 in Arizona (5.02 kWh/m^2 nationwide)” (Levinson & Akbari, 2010). However, due to reflecting sunlight during winter, white roofs can generate an inefficiency in the winter by keeping the roof isolated from sunlight. Overall, it was found that the added efficiency during the summer time was more impactful and the CO_2 reduction generated by this solution ranged from 1.07 kg/m^2 in Alaska to 4.97 kg/m^2 in Hawaii (3.02 kg/m^2 nationwide) (Levinson & Akbari, 2010).

- Lighting:

Many warehouses have storage racks that may block the natural light from windows and other openings in the structure of the building. Therefore, maintaining good visibility in a warehouse is vital and does require a significant amount of energy. Switching to LED lighting is considered one of the most important solutions due to LEDs significantly lower energy consumption. Migrating to LED lighting is estimated to save **40** % of energy when compared to high pressure sodium (HPS) light bulbs (Katzin et al., 2021).

- Mobile Material Handling Equipment (MMHE):

Mobile material handling equipment (MMHE) utilization and movement around the warehouse are considered key elements in warehousing operations. The movement of forklifts, order pickers, or automated storage and retrieval systems (AS/RS) plays an important role in defining the warehouse throughput and efficiency level. Therefore, it is important to study the possibility of introducing more efficient MMHEs not only to reduce the needed energy to operate the warehouse, but also to contribute to lowering the health and safety risks during operation. As majority of the energy consuming MMHE in the assigned two warehouses for this project are forklifts, we will run a comparison between the most available sustainable forklifts in the market:

    - Propane powered forklifts
    - Electric powered forklifts
    - Hydrogen powered forklifts

- Fixed Material Handling Equipment (FMHE):

Even though fixed material handling systems, such as conveyor belts or automatic sorting machines, are not considered one of the main areas of energy consumption in a warehouse, we believe that the number of FMHEs will increase with the focus on automation and throughput levels in warehouses and fulfillment centers. Adding sub-distribution control units to existing FMHEs to monitor and manage the energy consumption equipment can save up to 20% of energy while trouble shooting power quality problems to help reducing the downtime of the machines (ABB, 2022).

Aside from the available energy consumption reduction technologies, we are exploring in our project the feasibility and payback of generating clean energy on site. Sustainable energy generation solutions are wide and require a good understanding about the physical limitation in a building before having them considered as valid candidates. Wind and sun are considered the main sources feeding renewable energy generation solutions at a small scale (Zeng, 2011). For that reason, we will consider solar panels and micro wind turbines as potential candidates to be assessed and analyzed.

As for the available technologies related to water consumption, the market offers a wide range of solutions that can be summarized in the following categories:

- Water saving fixtures: mainly targeting water consumption in restrooms such as low-flow plumbing fixtures, waterless urinals, dual-flush toilets, and motion-detecting faucets (Inbound Logistics, 2013).
- Rainwater harvesting: with a simple technology, depending on the location and available harvesting area, a building can store a significant amount of their yearly water consumption from rain (The Renewable Energy Hub, 2022).

The strands of literature we analyzed helped inform the methodology that we will follow in this project.

3. METHODOLOGY

In developing our methodology, we decided to use the GHG protocol guideline. Methodology development was also aligned with the expectations of Maersk. Based on the discussions with Maersk and MIT scientific advisors, the following steps were defined:

1) Object identification
2) Baseline definition
3) Scope definition
4) Sources of emissions identification
5) Data gathering
6) Quantification of GHG emissions
7) Identification of sustainable solutions
8) Economic and environmental impact assessment for sustainable solutions
9) Prioritization of sustainable solutions
10) Guideline development for roll out of sustainable solutions

Object identification. It refers to selection of specific facilities to be considered as an object of the study. Two facilities were suggested by Maersk: Facility A, as a fulfillment facility and Facility B, as a transload one. Both of warehouses are located in New Jersey.

Baseline definition. The baseline for this capstone is defined as emissions generated as per November 2022 prior introducing the sustainable solutions: set of assets, water management system conditions, lighting system, etc. A baseline level of emissions is needed for (1) understanding the impact out of implemented or suggested sustainability initiatives and (2) reporting GHG budget.

Scope definition. Scope definition refers to agreement on which of the 3 emissions scopes are covered by the project. It was agreed that the capstone would cover only scope 1 and scope 2 emissions.

Sources of emissions identification. Several emissions sources were analysed to identify potential sources of emissions at the warehouse level. This was followed by analysis of a list of assets that exist in Maersk warehouses. Mentioned list was provided by our sponsoring organization. The list of sources needs to be verified with warehouse managers when running on site visits of facilities.

Data gathering. To facilitate the subsequent steps of our methodology, we continued gathering data from three distinct sources. Firstly, we collected data from Maersk, which provided us with information on asset utilization, fuel and utility consumption, and associated costs. This data was gathered through 20 interviews with company representatives and two on-site visits to selected warehouses. Secondly, we gathered external data from 108 open sources, such as industry reports, scientific articles, companies' reports, and websites, to obtain insights into current trends and specific sustainable solutions. Finally, we obtained data on the performance and costs of potential solutions from 13 different solution providers with which we held more than 30 interviews.

Quantification of GHG emissions. In terms of GHG emissions quantification, it is important to understand the contribution of each asset to the total emissions value. To quantify emissions from scope 1 emissions sources, two parameters are required: fuel consumption and emission factor for consumed fuel. Considering there are no records of fuel consumption by each asset, we estimated it using the following assumptions. We considered the normative fuel consumption of mentioned assets and multiplied it by its estimated utilization level. Assets' normative consumption values were obtained from relevant equipment manufacturers or industry reports. Estimated utilization levels were confirmed with warehouses' managers. Obtained results were validated with records of fuel consumption at each warehouse level with warehouse managers.

Scope 2 emissions were quantified considering the records of electricity consumption and grid-related emission factor. There are no records for the electricity consumption by each asset at the warehouse level. Therefore, we defined expected electricity consumption in kwh considering provided utilization levels by assets. Normative electricity consumption, provided by equipment manufacturers, was applied to obtained values.

Identification of sustainable solutions. We analysed applicability of identified solutions to the specifics of operations of each warehouse. We also analysed each solution considering current logistics industry practices, described in the "Available solutions to decrease or offset GHG emissions" section of this document, to estimate approximate outcome out of each solution implementation.

Economic and environmental impact assessment for sustainable solutions. Implementation of each solution was assessed considering two factors: (1) economical – payback, considering costs and value of GHG tax, and (2) environmental – impact on GHG emissions level. Maersk confirmed that payback and environmental impact would be considered as 2 KPIs for the purpose of sustainability solutions assessment.

Prioritization of sustainable solutions. Upon the completion of assessment of payback and environmental impact of each solution, total values for both KPIs were provided for each solution. This step leads to ranking of all solutions based on their potential impact.

Development of suggestions for rollout of sustainable solutions. We provided suggestions in terms of proper roll out of sustainable solutions based on records of logistics industry players' practices as well as indications of equipment manufacturers. Project results delivered through this methodology contribute to the main goal of this research: retrofitting of existing warehouses to a sustainable level.

4. RESULTS

To determine the most effective strategies for achieving sustainability in warehouse operations, we first needed to identify the primary sources of emissions at each warehouse under consideration. By pinpointing these emissions sources, we were able to gain a better understanding of the areas that require offsetting through the implementation of sustainable solutions. This comprehensive analysis allowed us to develop tailored approaches that directly address the specific environmental challenges faced by each warehouse, thereby maximizing the potential for achieving sustainability in their operations.

Through a thorough analysis of the data provided by the organization and consultations with subject matter experts, we identified the following key sources of emissions in warehouse operations:

- Scope 1 Emissions:
  - Propane: Forklifts are a significant source of propane emissions.
  - Diesel: Yard tractors contribute to diesel emissions in warehouse operations.
- Scope 2 Emissions:
  - Forklifts: Electric forklifts contribute to indirect emissions through electricity consumption.
  - Scissor Lifts: The use of electric scissor lifts also generates indirect emissions.
  - Scrubbers: Industrial scrubbers consume electricity, resulting in indirect emissions.

- Lights: Lighting systems in the warehouse consume electricity, contributing to Scope 2 emissions.
- Heating / cooling: limited to a small area dedicated to office workers.

By identifying these emissions sources, we can target specific areas for improvement and implement sustainable solutions to reduce the overall environmental impact of warehouse operations. Thus, in Table 1 we have considered several areas for potential improvement, including forklifts, solar energy, wind turbines, yard goats, HVLS fans. These solutions have been identified as having significant potential for enhancing our sustainability efforts, and we will explore them in greater detail to determine their feasibility and effectiveness in meeting sustainability goals.

Table 1

List of Potential Sustainable Solutions to Offset Identified Emissions' Sources

Scope	Source of emissions	Potential solutions	Status	Worth considering
Scope 1	Propane forklifts	Forklifts working on clean sources of energy	Partially implemented in Facility A, not implemented in Facility B	Worth
	Diesel yard goats	Electrified yard goats	Not implemented	Worth
Scope 2	Lights	LED lights, sensors	Implemented	Not worth
	Forklifts and other material handling equipment	Clean sources of energy: solar / wind	Facility A, implemented solar energy Facility B: not implemented	Worth
	Heating / cooling	HVLS fans	Not implemented	Worth
		Smart windows	Not implemented, no windows in warehouses	Not worth
		Smart thermostats	Not implemented, facilities are not heated / cooled	Not worth

		Loading dock seals	Implemented	Not worth
		Infrared heaters	Not implemented, facilities are not heated / cooled	Not worth
		Cool roofs	Not implemented, expensive solution (~10 USD per sq.ft), building not cooled	Not worth

4.1. Forklifts

4.1.1. Solution Overview

Forklifts are heavy-duty industrial vehicles used for lifting, moving and stacking materials, products and equipment in warehouses, factories and other industrial settings. They are designed with a forked platform or a lifting device that can raise and lower loads vertically and move them horizontally with ease. Forklifts are commonly used in warehousing operations as they increase efficiency and productivity by allowing workers to move large quantities of goods quickly and safely. They are particularly useful for moving heavy and bulky items that would otherwise require significant physical effort or time to move manually. Forklifts can also be used to load and unload goods from trucks and transport them to different areas of the warehouse.

Despite the remarkable progress made by companies in automating their warehouse operations with fixed material handling equipment, the demand for mobile material handling equipment is expected to grow at a CAGR of 5.7% until 2030, from a global market size valued at 213 billion USD (Grand View Research, 2022). This underscores the need to evaluate the environmental impact of such equipment on the carbon footprint of a warehouse.

As the world moves towards a more sustainable future, the trend of making vehicles more environmentally friendly has also affected forklifts. There are now three types of forklifts based on sustainability initiatives: electric, propane and hydrogen.

- Electric forklifts are powered by rechargeable batteries and emit no emissions on site, making them a clean and quiet option. They are best suited for indoor applications as they have limited run time and require a charging station.
- Propane forklifts run on propane gas, which burns cleaner than gasoline or diesel and produces lower emissions. They are suitable for both indoor and outdoor use and have a longer run time than electric forklifts.
- Hydrogen forklifts use fuel cells to convert hydrogen into electricity to power the vehicle, emitting only water vapor as a byproduct. They are still relatively new to the market and have a higher initial cost but are considered the most environmentally friendly option (subject to a clean hydrogen manufacturing process) (Flux Power, 2022). The fact that hydrogen driven forklifts is a relatively new solution explains the lack of available sources that review their effectiveness.

4.1.2. Comparison Between Propane, Electric and Hydrogen Forklifts

Analysis of attractiveness as well as limitations of mentioned types of forklifts can be executed via economic, safety, operational, charging infrastructure and environmental perspectives. For the purpose of comparison, we took electric forklifts as the baseline due to the fact they are considered by majority of sources as the most sustainable solution as well as they take majority of total sales of forklifts in the United States (61% of forklifts purchased in 2021 were electric driven) (FirstEnergy, 2022).

Cost of operating a forklift. One of the key performance indicators that we are considering in this project is payback. When evaluating the cost of the forklift, it's important to take a total cost of ownership perspective, rather than just looking at the purchase price. This means considering all costs associated with owning and operating the forklift over its entire lifespan, including maintenance, repairs, fuel, and other expenses.

Thus, electric forklifts cost more upfront than propane forklifts. For example, a 5,000 lb. cushion-tire propane lift truck costs between 24,000 USD and 30,000 USD, while an equivalent electric lift truck costs between 35,000 USD and 40,500 USD (Conger, 2021). But, from an operational cost point of view, some sources state that operating electrified vehicle can be up to 75% cheaper compared to the operating costs of propane driven vehicles (FirstEnergy, 2022), and most operations can expect to recoup their costs from an electric lift truck within two years of usage. Lower operational costs of electric forklifts are due to lower maintenance costs as well as cheaper electricity cost compared to propane. Propane forklifts require a regular maintenance, which includes:

- Oil changes.
- Engine tune-ups.
- Cooling system top-offs.
- Air/fuel mixture adjustments.
- Filter replacements.

On average, the maintenance cost per hour for electric forklifts is about 1.25 USD, whereas it is 2.00 USD for propane forklifts (FirstEnergy, 2022). This translates to an overall decrease of almost 40% in maintenance costs when electric forklifts are used.

Hydrogen driven forklifts are the most expensive ones. The cost of 5000 lb. hydrogen fuel cell forklift can range from 75,000 U|SD to 100,000 USD or more, depending on the manufacturer and model. Additionally, according to the US Department of Energy, the cost of hydrogen fuel can range from 12 USD to 16 USD per kilogram, which is roughly equivalent to the energy content of one gallon of gasoline. In comparison, the average price of electricity in the US is around 13 cents per kilowatt-hour, which is equivalent to around 4 USD per gallon of gasoline (Alternative Fuels Data Center, 2020).

Hydrogen fuel cell forklifts have more complex components and systems than electric forklifts, which can result in higher maintenance costs. However, hydrogen fuel cells are designed to be more durable and reliable than traditional lead-acid batteries used in electric forklifts. This can result in longer service life and lower replacement costs in the long run. But, considering that majority of modern forklifts are supplied with lithium-ion batteries due to significant advantages if comparing with lead-acid solution (faster cooling time, faster charging, and lower maintenance costs), the main advantage of hydrogen fuel cell over electric forklifts becomes obsolete (Hy-Tek, 2023). According to a study conducted by the National Renewable Energy Laboratory (NREL), the maintenance costs of hydrogen fuel cell forklifts were found to be slightly higher than electric forklifts, but lower than propane or diesel-powered forklifts. The study estimated that the maintenance costs for a hydrogen fuel cell forklift were approximately 1.58 USD per hour of operation, while the maintenance costs for a lead-acid battery electric forklift were approximately 1.25 USD per hour of operation (National Renewable Energy Laboratory, 2019).

Another concern associated with hydrogen forklifts is due to the cost of storage and fueling infrastructure needed in a warehouse that can reach 1M USD per site as per some of the sources (Bristowe & Smallbone, 2021). The NREL study estimated that the annualized cost of hydrogen infrastructure (including the capital, operating, and maintenance costs) is 3700 USD per lift truck. NERL made the estimation assuming a fleet size of 58 units (National Renewable Energy Laboratory, 2019).

Safety concerns. Electric forklifts have a safety advantage over propane forklifts because they do not involve combustible fuel. While propane is generally stable, it can leak from tanks and create a fire or explosion hazard. Propane tanks can also be punctured, which is why OSHA requires designated areas and storage racks for propane tank storage (Occupational Safety and Health Administration, 2023). Electric forklifts eliminate the risk of cold burns or impact injuries from changing propane tanks. However, electric forklifts do have their own hazards. Industrial batteries can cause injuries, such as acid burns or impact injuries, during installation or removal. Additionally, those working with batteries or chargers may be at risk of electric shock if proper safety precautions are not taken, although lithium-ion batteries are generally safer than lead-acid ones (Occupational Safety and Health Administration, 2019).

Compared to electric and propane forklifts, hydrogen-powered forklifts pose a greater risk due to hydrogen's highly flammable nature and the lack of odor, which makes it difficult to detect leaks without the installation of sensors. This means that additional safety precautions and measures are necessary when using hydrogen forklifts to minimize the risk of accidents and ensure safe operation (Zohuri, 2019).

Operational aspect. Compared to electric lift trucks, propane forklifts have better runtime and torque, which allow them to operate more efficiently on inclines and slopes and boost productivity. One of the major downsides of electric forklifts is that they gradually lose power and runtime as the battery drains, requiring a full 8-hour recharge and cooldown period before reuse (applicable to lead-acid batteries, for lithium-ion charging time is improved overall with fast and opportunity charging solutions available). Propane forklift, on the other hand, can be brought back to operation easily by replacing a propane tank. This operation typically does not require much time.

In its turn, electric forklifts offer many benefits to operators, such as minimal smells, gases, and liquids to deal with, lower noise and vibration levels reducing drivers' fatigue, and better maneuverability due to their shorter frames and wheelbases. Additionally, by removing the propane tank from the rear, electric forklifts gain an advantage in visibility.

Hydrogen-based forklifts outperform electric ones in terms of refueling time, taking less than 3 minutes as opposed to up to 16 hours (Linde Material Handling, 2016).

Charging infrastructure. A significant limitation for electrical forklift is the requirement for a dedicated area for a charging infrastructure. This can be a strong factor preventing warehouses with limited space from moving to electrified vehicles. Oppositely, propane tanks and hydrogen fuel can be stored outside of facility which eliminates the issue with the available area inside of warehouse. But there is a specific limitation for hydrogen and propane related solutions as they require certifications and sometimes investment to storage infrastructure. The National Fire Protection Association (NFPA) has established specific codes and standards for the storage and handling of hydrogen or propane, which include requirements for fire protection, emergency planning, and employee training.

Fast charging stations were developed as a response to the issue with limitation of available space inside of facility. They can recharge electric forklifts much more quickly than traditional charging stations, which can eliminate the need for additional charging stations.

Environmental impact. Electric lift trucks are emission-free since they eliminate the combustion cycle. This is a benefit to the environment and the safety of individuals who work closely with forklifts.

Despite propane forklifts being designed for indoor use, there are still risks associated with emissions exposure. This is especially true in confined spaces like semi-trailers and railcars where there is a greater risk of asphyxiation. Therefore, it is essential for facilities to install carbon dioxide monitors in areas where propane lift trucks are used. This ensures that both operators and pedestrians can be quickly notified of any carbon dioxide build-up and evacuate before any issues arise.

Hydrogen forklifts, same as electric, are the “green” forklift options because they don’t produce any harmful exhaust. Hydrogen fuel cells release water vapor into the air, which is either absorbed or stored in a reservoir. However, the sourcing of the hydrogen muddles the low emissions claim. Hydrogen is produced by reforming natural gas, a process that emits more CO2 into the atmosphere than simply burning the gas would (Zohuri, 2019). As a potential solution, hydrogen generated by energy from sustainable source (wind and solar) is considered as a sustainable type of hydrogen, although it drives the cost of hydrogen higher. Detailed comparison of propane, electric and hydrogen forklifts is in Table 2.

Table 2

Comparison of Propane, Electric and Hydrogen Forklifts

Factor	Propane forklifts	Electric forklifts	Hydrogen forklift
Forklift operating cost	Lowest upfront cost, highest TCO	Medium upfront cost, lowest TCO	Highest upfront cost, medium TCO
Safety risks	Propane leak from the tank: fire hazard	Low risk: electric shock. Acid spills and leaks for lead-acid batteries	Highly flammable, no odor
Operational aspect	Better runtime, high vibration levels, odor	Frequent recharging is needed, no smells, low vibration level Better maneuverability	Fastest refueling
Charging infrastructure	None, only propane storage place	Charging stations	Charging station Hydrogen storage
Environmental impact	Produce emissions of CO2 and other gases	No direct emissions at facility, total emissions are subject to grid structure	No direct emissions at facility, total emissions are subject to hydrogen manufacturing process

4.1.3. Payback and Environmental Assessment Methodology

Payback assessment. To run the comprehensive assessment of different options of forklifts, we must consider all major cost drivers associated with operating those vehicles. Those cost drivers include:

- Price of forklift
- Cost of relevant infrastructure
- Maintenance expenses
- Cost of fuel

- Value of carbon tax paid
- Available incentives

Payback assessment is done for forklifts of the same capacity: 5000 lbs. An important assumption is that the electric forklift will cover the same workload as alternative types of forklifts without any impact on charging time, due to considering a fast-charging solution and opportunity charging in this model.

Electric forklifts. Payback calculation of electric forklifts will be based on the assessment of purchasing price difference with propane forklifts and the value of savings while operating the vehicle.

$$Payback = \frac{C_e - C_p}{S_{fuel} + S_{maintenance} + S_{CT}}$$

Where:

Payback – expected payback of electric forklift

C_e– cost of electric forklift, USD

C_p– cost of propane forklift, USD

S_{fuel} – expected savings based on fuel consumption, USD

$S_{maintenance}$ – expected savings based on maintenance of vehicle, USD

S_{CT} – avoided carbon tax thanks to implementation of electric vehicle

For the calculation of cost of electric forklift, we need to consider special cost drivers:

$$C_e = Forklift + 2 * Battery + Taxes + Charging\ Solution - Incentive$$

Where:

C_e– expected purchasing price of 1 electric forklift, USD

Forklift – cost of 1 vehicle, USD

Battery – cost of 1 battery, USD

Taxes - Tax dollars due based on tax rate applied to all EV cost elements

Charging solution - Cost of charging infrastructure per vehicle ordered

Incentive - Total value of grants, vouchers, and tax credits that lower purchase price (or in effect act as a one-time benefit)

To assess the purchasing cost of propane forklift it is assumed that there are no additional cost drivers apart from the asset cost (charging infrastructure, tax benefits).

$$S_{fuel} = EH * PC * C_{propane} - \frac{EH * EC * C_{electricity}}{CE}$$

Where:

EH – engine hours

HC – propane consumption, lb. per engine hour

$C_{propane}$ – cost of propane, USD per lb

EC – electricity consumption, kwh per engine hour

$C_{electricity}$ – cost of electricity, USD per kwh

CE – charging efficiency, %

It is important to note that verifying the calculated propane consumption by comparing it with historical volumes is crucial. This can be done by dividing the recorded annual propane consumption at a particular facility by the total engine hours logged for all vehicles in that year. If the propane consumption in pounds per engine hour does not match the average figures provided, we recommend considering the propane consumption ratio as per historical records.

Regarding electricity consumption, we recommend obtaining the expected electrical consumption directly from the equipment manufacturer. If this information is not available, we suggest using the provided electricity consumption values. Same logic applies to hydrogen forklifts in a following section.

$$S_{maintenance} = EH * M\&RC_{propane} - EH * M\&RC_{electric}$$

Where:

EH – engine hours

$M\&RC_{propane}$ – maintenance and repair cost of propane forklift, USD per engine hour

$M\&RC_{electric}$ – maintenance and repair cost of electric forklift, USD per engine hour

We would like to emphasize that the most dependable method for calculating potential annual maintenance savings is to compare the actual or projected cost of annual preventive maintenance for propane forklifts with the cost of annual preventive maintenance for electric vehicles as specified in the maintenance contract with the equipment manufacturer. If these figures are unknown, we recommend using the provided formula. Same logic applies to hydrogen forklifts in a following chapter.

$$S_{tc} = \left(PC * EF_{propane} - EC * GF_{electricity}\right) * Tax$$

Where:

PC – registered annual propane consumption of 1 propane vehicle, lb

$EF_{propane}$ – emissions factor for propane consumption, CO2 per lb

EC – expected annual electricity consumption for 1 vehicle based on registered fuel consumption, kWh

$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh

Tax – value of carbon tax, USD per ton of CO2

Hydrogen forklifts. Payback assessment for hydrogen forklifts will be done in the same way as for electric vehicles:

$$Payback = \frac{C_h - C_p}{S_{fuel} + S_{maintenance} + S_{CT} - IC}$$

Where:

Payback – expected payback of hydrogen forklift.

C_h– cost of hydrogen forklift, USD

C_p– cost of propane forklift, USD

S_{fuel} – expected savings based on fuel consumption, USD

$S_{maintenance}$ – expected savings based on maintenance of vehicle, USD

S_{CT} – avoided carbon tax thanks to implementation of hydrogen vehicle

IC – monthly infrastructure cost, USD per vehicle

To assess the purchasing cost of propane forklift it is assumed that there are no additional cost drivers apart from the asset cost. As for hydrogen forklift, it strongly depends on the approach a company decides to pursue: whether to consider the installation of hydrogen generator on site or supply hydrogen from 3rd parties and store it in a tank. Because the cost of storage infrastructure greatly varies depending on the fleet of forklifts, it was decided to consider this cost component separately as monthly extra cost of operating a hydrogen forklift.

$$S_{fuel} = EH * PC * C_{propane} - EH * HC * C_{hydrogen}$$

Where:

EH – engine hours

PC – propane consumption, lb per engine hour

$C_{propane}$ – cost of propane, USD per lb

HC – hydrogen consumption, kg per engine hour

$C_{hydrogen}$ – cost of hydrogen, USD per kg

$$S_{maintenance} = EH * M\&RC_{propane} - EH * M\&RC_{electric}$$

Where:

EH – engine hours

$M\&RC_{propane}$ – maintenance and repair cost of propane forklift, USD per engine hour

$M\&RC_{hydrogen}$ – maintenance and repair cost of hydrogen forklift, USD per engine hour

$$S_{CT} = \left(PC * EF_{propane} - HC * EF_{hydrogen}\right) * Tax$$

Where:

PC – registered annual propane consumption of 1 propane vehicle, lb

$EF_{propane}$ – emissions factor for propane consumption, CO2 per lb

HC – expected annual hydrogen consumption for 1 vehicle based on registered fuel consumption, kWh

$EF_{hydrogen}$ – emissions factor for hydrogen consumption, CO2 per lb

Environmental impact. For the case of Maersk, we consider either electrified or hydrogen driven forklifts to replace propane vehicles. In this case calculation of environmental impact goes directly from the difference of emissions from propane vehicles and those that are electrified or consume hydrogen. The most accurate method for emissions calculation is fuel based.

$$EI = (PC * EF_{propane} - EC * GF_{electricity}) * N$$

Where:

EI – expected annual environmental impact out of project implementation, CO2 tones

PC – registered annual propane consumption of 1 propane vehicle, lb

$EF_{propane}$ – emissions factor for propane consumption, CO2 per lb

EC – expected annual electricity consumption for 1 vehicle based on registered fuel consumption, kWh

$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh

N − number of vehicles in the fleet of warehouse

Similarly, impact assessment for hydrogen forklifts must be done the following way:

$$EI = (PC * EF_{propane} - HC * EF_{hydrogen}) * N$$

Where:

EI – expected annual environmental impact out of project implementation, CO2 tones

PC – registered annual propane consumption of 1 propane vehicle, lb

$EF_{propane}$ – emissions factor for propane consumption, CO2 per lb

HC – expected annual hydrogen consumption for 1 vehicle based on registered fuel consumption, kWh

$EF_{hydrogen}$ – emissions factor for hydrogen consumption, CO2 per lb

N− number of vehicles in the fleet of warehouse

4.1.4. Proposed Solutions for Selected Warehouses – KPIs Assessment

To assess potential outcome of replacement propane forklifts with electrified vehicles at the level of Facility A and Facility B, we contacted one of the key players of the global forklifts market. The company manufactures wide range of forklifts starting from traditional diesel vehicles finishing with more sustainable options, such as propane, electric and hydrogen driven forklifts. As for hydrogen vehicles, as per the company's feedback, they supply it only in Europe where infrastructure as well as availability of fuel is more advanced.

The limited availability of hydrogen forklifts for purchase in the United States remains a significant obstacle. Therefore, to compare the potential impact of implementing a fleet of hydrogen forklifts, we obtained costs from U.S.-based provider of hydrogen forklifts related solutions. However, to compare return on investment on hydrogen forklifts, we used relevant values for cost drivers from open sources. All inputs of parameters for payback assessment are specified in Table 3.

Table 3

Inputs of Parameters for a Simplified Payback Assessment with Sources

Parameter	Value	Source
C_e– cost of electric forklift, USD	50,204.00	Estimated pricing by forklift manufacturer
C_p– cost of propane forklift, USD	42,900.00	Estimated pricing by forklift manufacturer
C_h– cost of hydrogen forklift, USD	75,000.00	(Hydrogen Fuel News, 2022)
IC – annual infrastructure cost, USD per vehicle	3,700.00	(Metzger & Li, 2022)
Battery – cost of 1 battery, USD	8,898.00	Estimated pricing by forklift manufacturer
Charging solution - Cost of charging solution per vehicle ordered, USD	9,000.00	Estimated pricing by fast charging solution provider
EH – engine hours	2,912.00	Indications provided by warehouse managers (utilization, working schedule)
HC – propane consumption, lb per engine hour	6.00	(Toyota, 2020)
$C_{propane}$ – cost of propane, USD per lb	3.50	(Compare Propane, 2023)
EC – electricity consumption, kwh per engine hour	7.50	(AdapdaliftGroup, 2021)
$C_{electricity}$ – cost of electricity, USD per kwh	0.17	Electricity bills provided by warehouse managers
CE – charging efficiency, %	0.91	Kuhn et all, 2005
HC – hydrogen consumption, kg per engine hour	0.19	(Walker, 2021)
$C_{hydrogen}$ – cost of hydrogen, USD per kg	16.00	(Petrochemical, Chemical & Engineering, 2022)
$M\&RC_{propane}$ – maintenance and repair cost of propane forklift, USD per engine hour	2.00	(National Renewable Energy Laboratory, 2019)
$M\&RC_{electric}$ – maintenance and repair cost of electric forklift, USD per engine hour	1.25	(National Renewable Energy Laboratory, 2019)

Parameter	Value	Source
$M\&RC_{hydrogen}$ – maintenance and repair cost of hydrogen forklift, USD per engine hour	1.58	(National Renewable Energy Laboratory, 2019)
$EF_{propane}$ – emissions factor for propane consumption, CO2 per lb	5.72	(EPA, 2014)
$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh	672.80	(EPA, 2021)
$EF_{hydrogen}$ – emissions factor for hydrogen consumption, CO2 per lb	0.00	Assumed that hydrogen supplied was generated using renewable energy

Results of assessment for both facilities are present in Table 4.

Table 4

Results of Payback Assessment for Electrical and Hydrogen Forklifts

Parameter	Facility A, years	Facility B, years
Payback, electrical forklift	2.47	1.92
Payback, hydrogen forklift	4.49	3.15

The main reason for the differences in payback between Facility A and Facility B is due to Facility B's higher utilization of their fleet, which is specific to their operations. This results in a stronger impact of cost differences between operating propane forklifts and electric/hydrogen vehicles, due to higher electricity consumption and more frequent maintenance needed.

The better payback for electrical forklifts is present mostly due to the lower electricity cost and maintenance related expenses comparing with hydrogen-based vehicles. Following the formula for environmental impact assessment, we have the following volumes of tons of CO2 avoided per calendar year that are present in Tables 5 and 6.

Table 5

Results of Environmental Impact Assessment for Electric Forklifts

Facility	# of forklifts	Saving of CO2, tons per year, per vehicle	Total saving of CO2, tons per year
Facility A	9	17.13	154.18
Facility B	16	22.03	352.41

Table 6

Results of Environmental Impact Assessment for Hydrogen Forklifts

Facility	# of forklifts	Saving of CO2, tons per year, per vehicle	Total saving of CO2, tons per year
Facility A	9	23.80	214.20
Facility B	16	30.59	489.44

The main challenge with assessment of environmental impact of hydrogen forklift implementation is due to the fact it is not clear which process was used to produce hydrogen and which source of energy was used to produce it. As per the feedback of hydrogen forklifts' provider, they apply electrolysis through renewables, which brings the level of emissions to 0 kgs of CO2. For the purpose of environmental assessment, we considered scenario of clean source of energy to generate hydrogen.

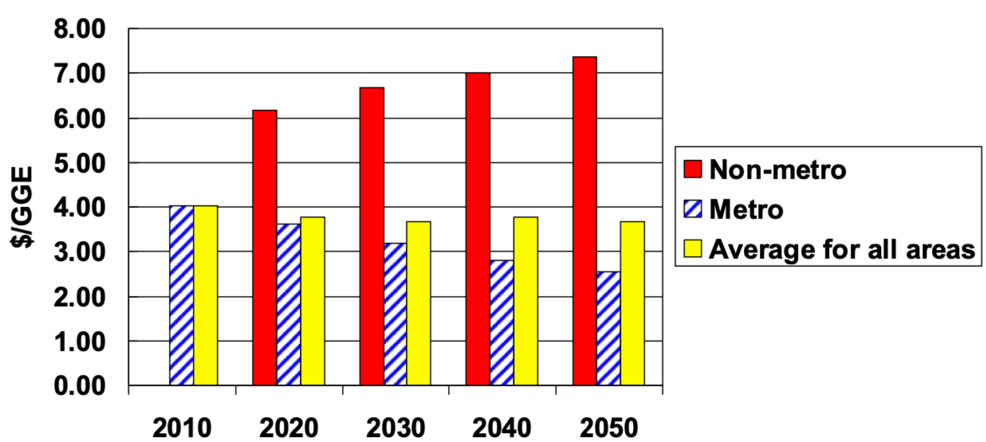
4.1.5. Way Forward

After researching all the three available options, we still find challenges in migrating to a hydrogen forklifts' fleet. Even though electric forklifts are well recognized among different sources as the most sustainable solution for material handling equipment, some of sources do consider hydrogen forklifts as strong competitors of electrified vehicles. Nevertheless, considering several currently present factors, implementation of hydrogen forklifts can be classified as challenging due to:

- Availability of forklifts for purchase: as per results of our research, none of biggest players of global forklifts' market provides hydrogen solution in the United States. Some of manufacturers have hydrogen vehicles in their portfolio, but focus on European market where availability of hydrogen is better if comparing with US.
- The significant investment in infrastructure makes the solution only valid for warehouses with a big number of forklifts.
- Availability of hydrogen as fuel: it has been reportedly stated that there are continuous challenges in the supply of hydrogen for consumers in the United States (Hydrogen Fuel Cell Partnership, 2020).
- Cost of hydrogen: hydrogen remains to be expensive, even though its cost has been significantly improving over the time and expected to continue improving (CBS, 2022).

Figure 1

Forecast of Hydrogen Cost Until 2050



Source: Singh, M., Moore, J., Shadis, W., Patterson, P. (2005). Hydrogen Demand, Production, and Cost by Region to 2050. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory and TA Engineering, Inc. for U.S. Department of Energy (EERE/PBA).

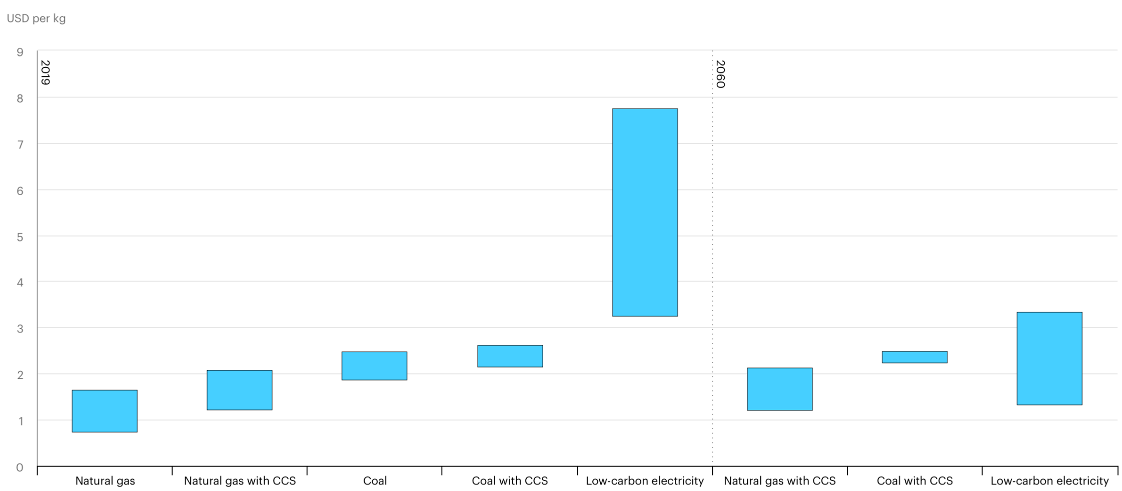
In general, the process of generation of hydrogen is costly even considering production from a natural gas. IEA claims that the cost of hydrogen generation using low-carbon electricity is significantly higher if comparing with low-carbon electricity, which makes majority of hydrogen manufacturers to stick to low-cost solutions. The European Commission has also validated the aforementioned pattern. As per the Commission's hydrogen strategy of July 2020, producing green hydrogen using renewable sources costs approximately 3 USD to 6.55 USD per kilogram. In contrast, hydrogen derived from fossils costs around 1.80 USD per kilogram, and blue hydrogen, which involves combining carbon capture with steam methane reformation of natural gas, costs roughly 2.40 USD per kilogram (S&P Global, 2023). Nevertheless, it is expected that cost of hydrogen generation from low-carbon electricity will fall significantly, but still the process will be more expensive than generation from the natural gas.

- Environmental impact: 95% of hydrogen is made from natural gas with or without the use of CCUS, which leads to NOx, SOx, Black Carbon or Particulate Matter (Zohuri, 2019). It can be produced using renewable sources, but this process is expensive. Even though some of hydrogen providers claim that they generate hydrogen via electrolysis through renewables, it still remains challenging to trace it due to supply chain visibility constraints (International Energy Agency, 2019).

- Scale of solution: Hydrogen forklifts provider communicated that they do not consider implementation of forklift solution as feasible for fleets with less than 40 vehicles.

Figure 2

Cost of Hydrogen as Per Different Sources

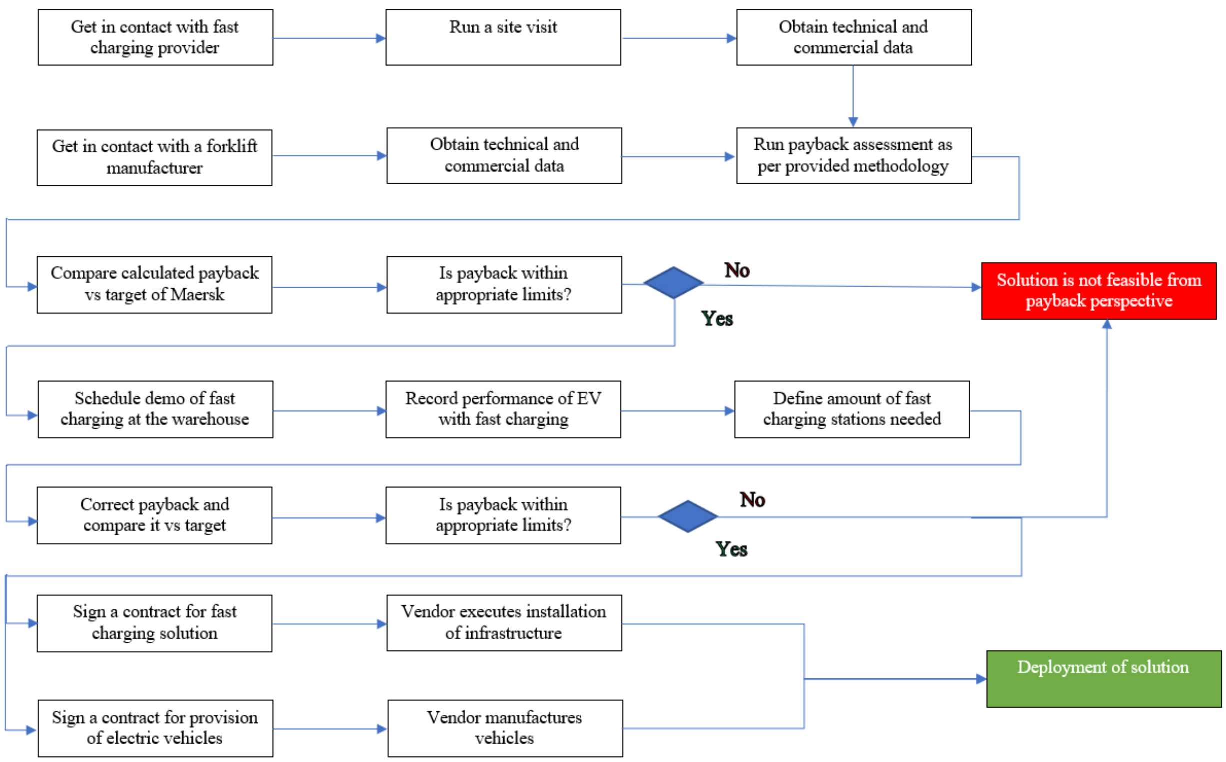


Source: IEA. (2019). *Global average cost of hydrogen production by energy source and technology, 2019 and 2050.* https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050

Based on the factors mentioned earlier, we believe that hydrogen forklifts have significant potential. However, given the current factors mentioned above, we do not recommend them as the primary solution for achieving sustainability in material handling equipment fleets at the assigned warehouses. Our analysis suggests that electric forklifts are the most suitable solution from a sustainability and cost standpoint.

Figure 3

Roadmap to Scale Forklifts to Other Locations



In terms of the way forward represented in Figure 3, we reinforce the importance of considering the fast-charging solution due to the following advantages:

1. Significantly smaller space needed compared to traditional charging stations.
2. Fast charging cycle.

Nevertheless, it is important to run a trial to understand what real charging cycle of solution for forklifts of a company is and which changes the company needs to undertake in terms of:

1. Shift and allocation of forklifts to take advantage of opportunity charging.
2. Number of charging stations needed on site.

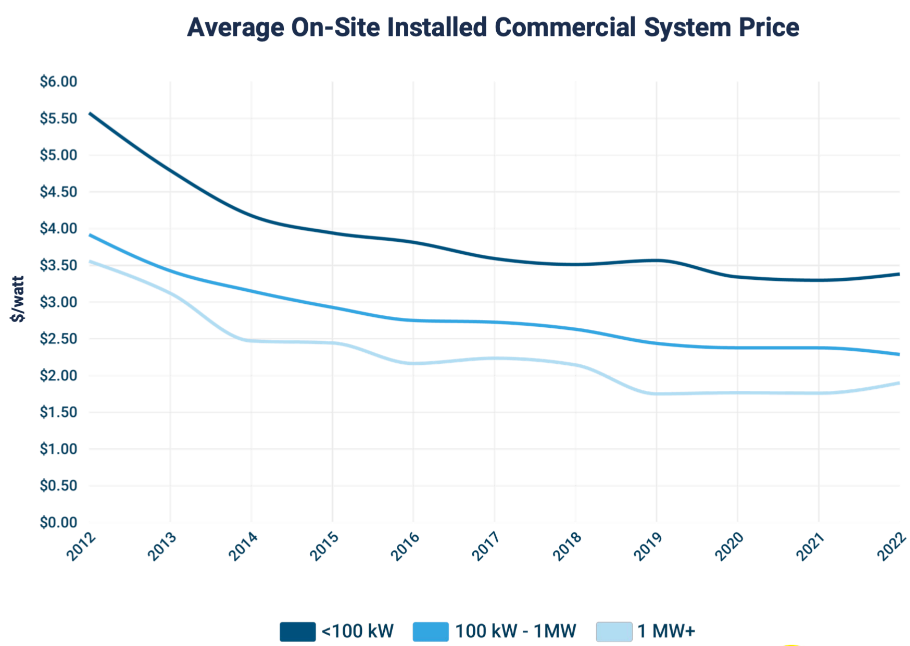
4.2. Solar Energy

4.2.1 Solution Overview

Solar energy presents an attractive and sustainable solution for warehouse operations due to its potential to reduce energy costs, minimize environmental impact, and provide a reliable source of clean energy. As warehouses typically have large roof spaces and high energy demands, harnessing solar energy through photovoltaic (PV) systems can be an effective way to address these challenges.

Figure 4

Dynamics of Average On-Site Installed Commercial System Price in the US



Source: Solar Energy Industries Association. (2022). Solar Means Business. https://www.solarmeansbusiness.com/

The popularity of solar energy is on the rise across various industry sectors. The shift towards solar power is driven not only by sustainability objectives but also by compelling economic factors. The increasing commercial interest in solar energy can be attributed to the significant reduction in on-site installation costs as per Figure 4, which have decreased by 51% in the last ten years. This trend has made solar energy more accessible and attractive as a power source for diverse market participants. Cost of off-site systems has also fallen so that they are competitive with all forms of energy generation.

4.2.2. Operational Models

All solar systems can be classified based on several criteria:

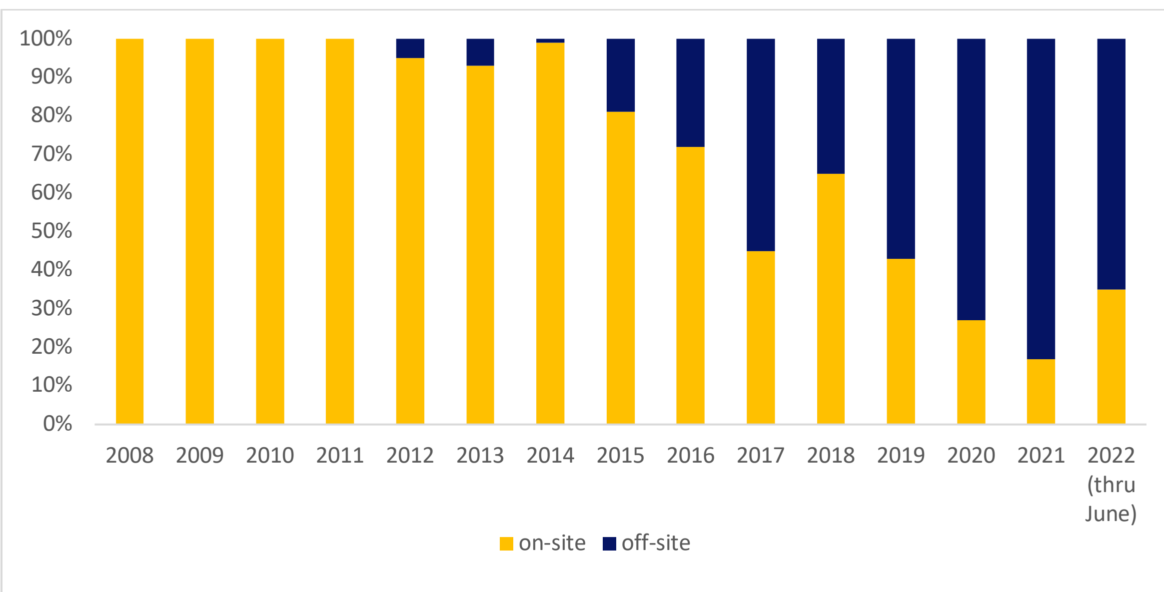
a) Considering the place of installation (see 4.2.2.1):
    a. On-site
    b. Off-site
b) Considering the ownership structure (see 4.2.2.2):
    a. Power purchase agreement based
    b. Owned
c) Considering the tracking site (see 4.2.2.3):
    a. Single axis
    b. Fixed
    c. Dual axis
d) Considering the mounting site (see 4.2.2.4):
    a. Rooftop
    b. Ground
    c. Carport
    d. Other

4.2.2.1. On-site and Off-site Installations

The change in solar industry trends can be clearly seen through the evolving procurement strategies. The solar energy market has been fully focused on on-site installations until approximately 2017. Off-site installations have grown significantly from 1.5 GW of total installed systems in 2017 to more than 10 GW of installations through June 2022, which resulted in 83% of all commercial solar capacity installed in 2022 being off-site. Trend that is seen in Figure 5 is driven by declining cost of solar installations, which makes the industry more attractive for new players that can develop community solar project field.

Figure 5

Dynamics of Proportion of On-Site and Off-Site Solar Installations in the US



Source: Solar Energy Industries Association. (2022). *Solar Means Business.* https://www.solarmeansbusiness.com/

Both types of installations differ from each other regarding specific benefits mentioned in Table 7.

Table 7

Comparison of Off-Site and On-Site Solar Projects

Parameter	Off-site	On-site
Model	Subscribe to community solar projects. Projects are owned either by utility or a private community solar company	Own the installed solar project or finance it via a loan, solar lease or a PPA (Power Purchase Agreement)
Billing	Pay per kwh of production from the community solar project and receive monetary credits that lower the electricity bill	On-site metering allows storage of excess energy by sending it back to the grid. You pay for the net amount of electricity you use during a billing period
Property ownership	Not required	Required
Contract length	From short as a year to as long as 25 years	Solar lease and PPAs are typically between 20-25 years
Operations and maintenance	Responsibility of the community solar project administrator	If you own – you run it. If it is owned by a solar company, they are responsible for maintenance
Property value	Has no impact	Increasing
Tax benefits	Not available	Available
Backup power	No	Battery storage
Environmental impact	Offsets emissions indirectly	Allows businesses to receive solar energy directly and reduce building emissions

4.2.2.2. Ownership Structure

For on-site installations the two most commonly considered approaches are:

1) direct ownership of the system with retention of associated tax credits

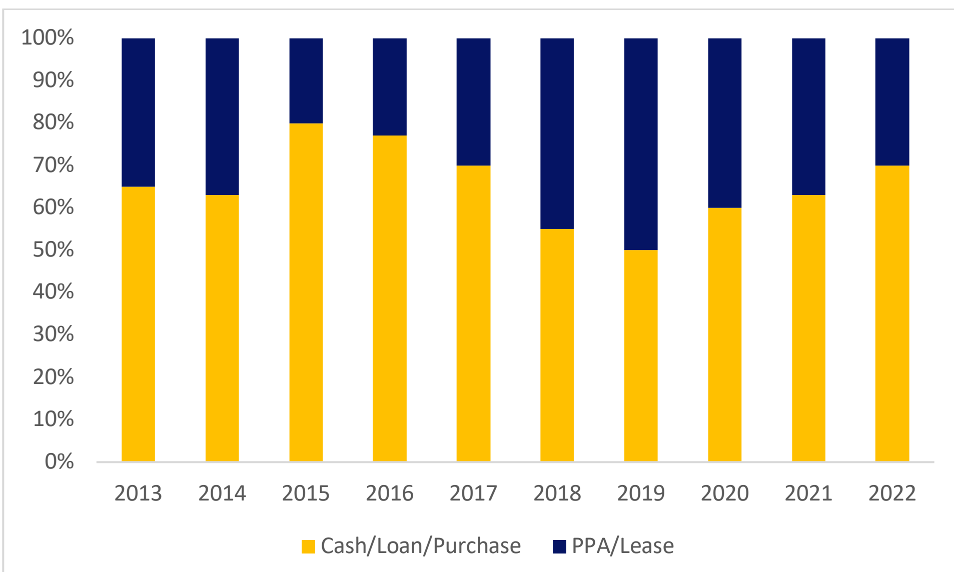
2) the approach where a third party installs the system on site but keeps the ownership over the system and sells generated electricity to the building owner based on power purchase agreement.

Direct ownership systems are financed upfront, while third-party systems have some or no up-front costs, though they require a specific contractual basis such as a power purchase agreement or solar lease.

The dynamics of change of projects' distribution as per financing structure in the United States in 2013-2022 is mentioned in Figure 6.

Figure 6

Dynamics of Financing Structure of Solar Projects in the US



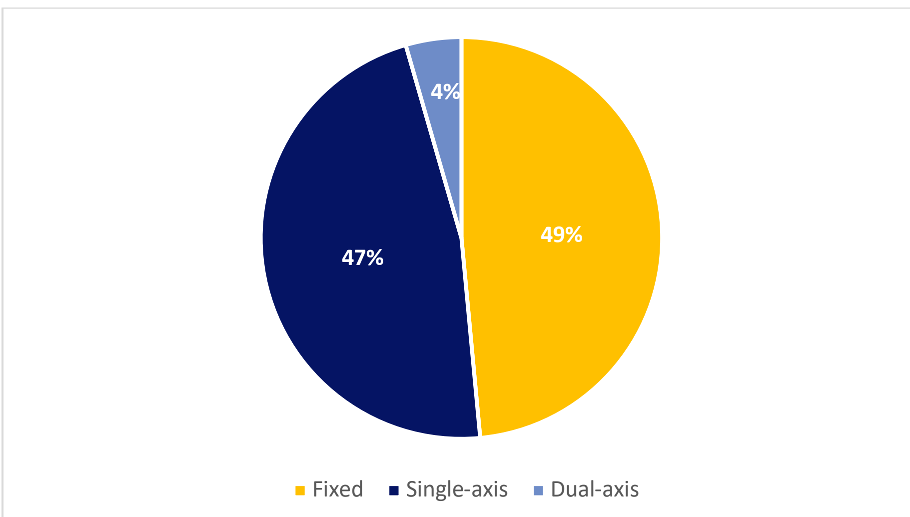
Source: Solar Energy Industries Association. (2022). *Solar Means Business.* https://www.solarmeansbusiness.com/

4.2.2.3. Tracking Site

Generation of electricity by a solar panel system depends on orientation of panels' location and in the case of single and dual axis systems, ability to track the sun during the daytime. Because solar system operates better when oriented directly towards the sun, some systems use sun tracking technology which increases the output in terms of generated energy. According to U.S. Energy Information Administration, distribution of fixed and single-axis solar installations is equal in the US. Although, together single-axis and dual-axis systems make up the majority of systems installed in the US as per Figure 7 (U.S. Energy Information Administration, 2017).

Figure 7

Distribution of Solar Projects Based on Tracking Type in the US



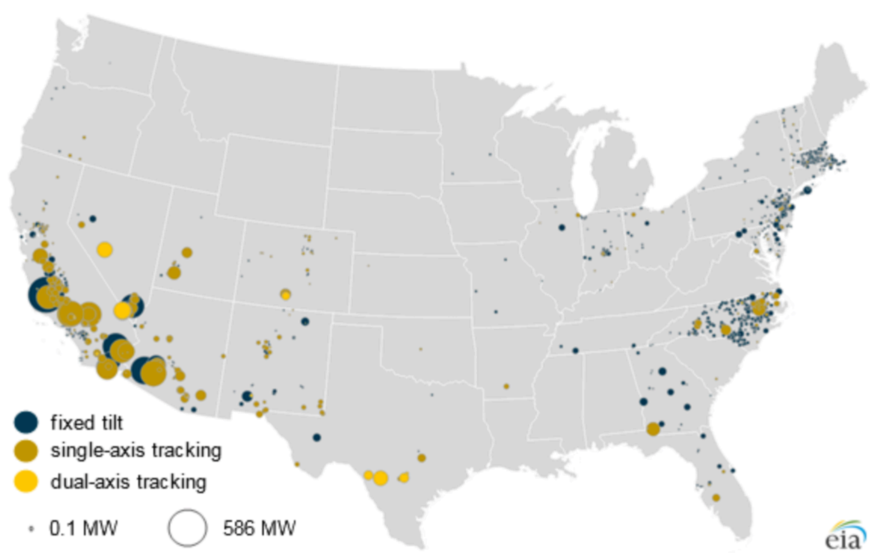
Source: Solar Energy Industries Association. (2022). *Solar Means Business.* https://www.solarmeansbusiness.com/

Because of the cost of the different solar systems as well as differences in solar insolation, solar tracking systems can be not the most economic ones. Solar insolation, also known as solar irradiance, is a measure of the amount of solar energy that reaches a specific area on Earth's surface over a given period of time. It is usually expressed in watts per square meter (W/m^2) and represents the electromagnetic radiation, including both visible light and other wavelengths, emitted by the sun. Solar insolation varies due to factors such as geographical location, time of day, season, and atmospheric conditions. It is a crucial parameter for determining the efficiency and effectiveness of solar energy systems, as it directly influences the amount of solar energy available for conversion into electricity or thermal energy.

The map in Figure 8 shows the distribution of fixed, single-axis and dual-axis systems across the United States, where we can see the Northern States mostly represented by fixed tilt systems (U.S. Energy Information Administration, 2022).

Figure 8

Geographical Distribution of Solar Projects Based on Tracking Type



Source: Solar Energy Industries Association. (2022). *Solar Means Business.* https://www.solarmeansbusiness.com/

Single and dual-axis systems tend to be implemented more in the states with higher solar radiation due to a higher expected output of solar energy: it is worth installing tracking systems in the states with higher solar irradiance, where it is possible to generate more energy out of the presence of tracking.

Considering the average level of irradiation in the US as well as costs of the relevant solar systems, we get the following comparison of annual energy savings and estimated payback period for a standard 4-kilowatt system (costs do not cover installation). Single-axis tracking systems lead to 30% higher energy savings vs fixed tilt system, although the payback period is higher due to higher installation cost of the mentioned system. Dual-axis tracking systems seem to be only ~8% more efficient (considering annual energy savings) if comparing with the single axis systems. Considering the mentioned factors, solar systems with tracking tend to be implemented in the states with higher solar irradiance to maximize the potential energy savings.

Table 8

Expected Cost of 4-kilowatt Solar System Based on Tracking Type

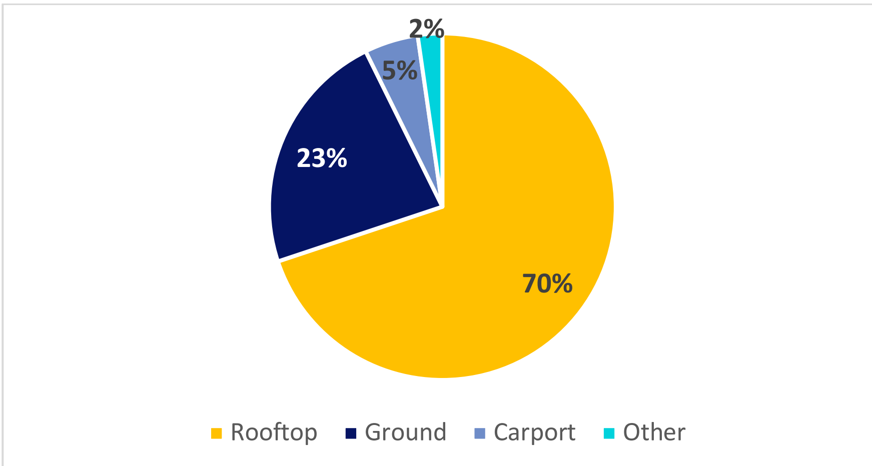
Solar system type	System cost (USD)	Annual energy savings (USD)	Estimated payback period
Fixed ground-mounted system	14,625	1,100	13 years
Ground-mounted system with single axis tracker	22,125	1,430	15.5 years
Ground-mounted system with double axis tracker	29,625	1,540	19 years

Source: Solar Reviews. (2021). *Are Solar Axis Trackers Worth the Additional Investment?* https://www.solarreviews.com/blog/are-solar-axis-trackers-worth-the-additional-investment

4.2.2.4. Mounting Site

Figure 9

Distribution of Solar Projects Based on Mounting Site



Source: Solar Energy Industries Association. (2022). *Solar Means Business.* https://www.solarmeansbusiness.com/

Chart in the Figure 9 shows the biggest number of installed systems tends to be installed on a rooftop, although the ground-based systems portion is increasing. Roughly 23% of all on-site capacity is ground mounted, up from 16% at the end of 2018. The mentioned increase is driven by the need in solar systems with the higher capacity.

4.2.3. Limitations to be Considered

The attractiveness of solar panels as a solution for power generation is primarily determined by two key factors: solar irradiance and incentives. Solar irradiance, or the amount of solar energy reaching a specific location, greatly influences the efficiency and effectiveness of solar panels in generating electricity or thermal energy. Additionally, incentives, such as tax credits, rebates, and other financial support programs, can significantly enhance the economic viability of solar energy systems, making them a more attractive option for businesses and individuals.

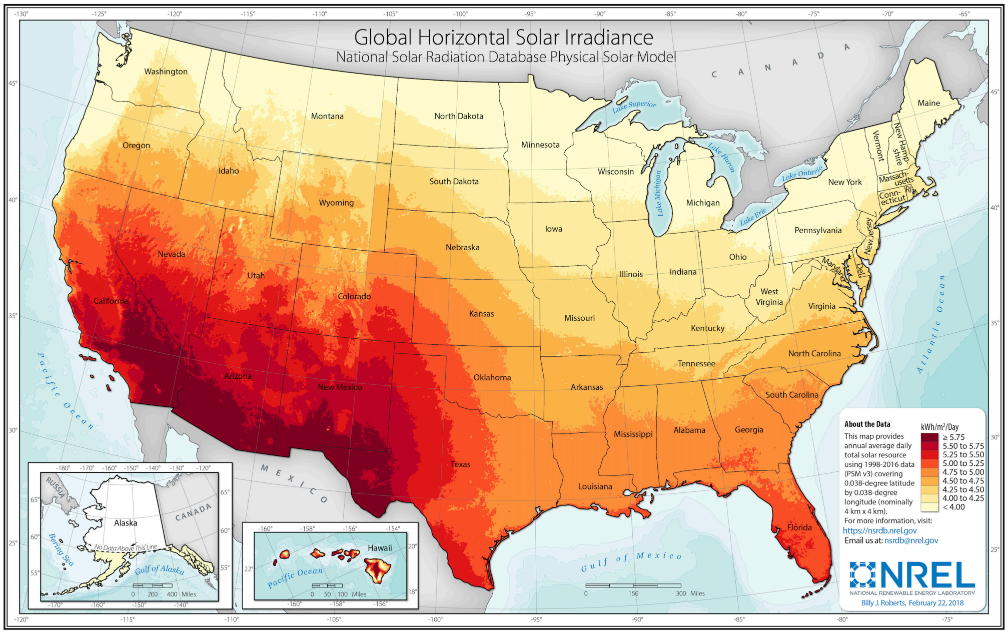
Time of day and location influence the availability and intensity of solar radiation on the Earth's surface. At solar noon on clear, cloudless days, when the sun is at its highest apparent position in the sky, the intensity of solar radiation is greatest at any location.

Insolation is a measure of how much solar radiation is received on a given surface area during a given period based on the following factors: latitude, climate and weather patterns.

The amount of solar radiation received by locations in lower latitudes and in arid climates is generally greater than that at other locations (Figure 10). Insolation levels at the surface are affected by clouds, dust, volcanic ash, and pollution in the atmosphere. Buildings, trees, and mountains may shade a location during different times of the day in different months of the year. Seasonal (monthly) variations in solar resources increase with increasing distance from the earth's equator. The map below shows the average annual solar irradiance in kWH/m2/day. Red zones represent the area with the strongest irradiance. The general rule is the more solar irradiance is present in a specific zone, the more solar energy is generated by the solar panels. Interesting dependency is seen with implementation of solar system type (fixed tilt, single-axis or dual-axis). Solar tracking systems tend to be implemented in the states with higher solar irradiance (5.00 kWh/m2/day and more).

Figure 10

Solar Irradiance Levels in the United States



Source: National Renewable Energy Laboratory. (2022). *Solar Resource Maps.* https://www.nrel.gov/gis/solar-resource-maps.html

Another factor to be considered is the level of incentives introduced by a specific state. Federal Solar Tax Credit system was introduced at the federal level in the US in 2006, and it has been continually extended by Congress. It allows the owners of building to claim 30% of the total installation cost of solar project on federal income taxes. At the same time, some states offer tax credits similar to the one from the federal government. Both combined they can generate a significant incentive to go solar. Currently 35 states have incentives implemented at the local level, which differ based on their strength (Grant, 2022). The top 10 states based on the quantity of tax incentives are:

- New York
- Rhode Island

- Iowa
- Connecticut
- Maryland
- New Mexico
- Colorado
- Massachusetts
- New Hampshire
- New Jersey

Table 9

Summary of Incentives Available for Solar Projects

State	Net metering	Sales tax	RECs	Property tax exemption	Total # of incentives*
New York	Yes	4% exemption	Yes	No	74
Rhode Island	Yes	7% exemption	Yes	Yes	31
Iowa	Yes	6% exemption	No	Yes	41
Connecticut	Yes	6.35% exemption	No	Yes	40
Maryland	Yes	6% exemption	No	Yes	49
New Mexico	Yes	No	Yes, some counties	Yes	37
Colorado	Yes	Yes	Some counties	Yes	69
Massachusetts	Yes	Yes	No	Yes	56
New Hampshire	Yes	No	Yes	Yes	36
New Jersey	Yes	6.625% exemption	Yes	Yes	36

There are different types of incentives available as per Table 9, however there are some of them that are the most frequent and most valuable in terms of economical outcome:

- Net metering: system owner can take advantage of the state's net metering program to sell energy generated back to the grid.
- Sales tax: state does not tax the cost of solar system equipment.
- RECs (renewable energy credits): exists typically in a form of monetary compensation of each kwh generated.
- Property tax exemption: increase in property value due to solar system installed is not taxed by the state.

4.2.4. Available Transaction Formats for Financing

Based on conducted research and discussions with major solar energy market players in New Jersey, two transaction formats have emerged for on-site solar energy solutions involving interactions with providers.

- **Roof Lease Agreement:** Solar energy provider will develop, build, fund, own and operate the projects and pay Maersk an annual rent payment for hosting the projects. Main benefit is the ability to cover a portion of the cost of energy consumed from the grid and offset the emissions generated from the grid.
- **Power Purchase Agreement:** Solar energy provider will develop, build, fund, own and operate the project. Maersk will purchase all the power produced from the system at a pre-determined rate (USD/kWh) for an agreed upon term.

Each transactional format has benefits and disadvantages presented in Table 10.

Table 10

Benefits and Disadvantages of PPA and Roof Lease Agreement

Parameter	Solar PPA	Solar Lease
Monthly payment	Fixed price **per kilowatt-hours (kWh)** for power generated.	Fixed **monthly ‘rent’** for using solar panels.
Term length	20-25 years	10-25 years
Restrictions	A facility owner can neither own nor lease the solar PV system, and developers keep all solar renewable energy credits (SRECs).	A facility owner leases the solar panel and components. You may be able to negotiate to keep SRECs for yourself.
Types	- On-site/Behind-the-Meter PPAs: Agreements where solar energy is generated and consumed at the same location. - Retail-Sleeved PPAs: Contracts that involve a utility acting as an intermediary between the solar producer and end user. - Virtual PPAs: Financial agreements that don't require physical delivery of electricity, but instead involve trading energy credits.	Capital lease Operating lease

4.2.5. Proposed Solutions for Selected Warehouses – KPIs Assessment

To assess the potential outcome of implementation of solar solution for both of the selected warehouses, we contacted one of the biggest providers of solar energy solutions in New Jersey. As per results of discussions with provider as well as specifics of both facilities, the following systems were offered by provider for installation on the roofs of both buildings (Table 11).

Table 11

Overview of Solar Systems' Capacities

Parameter	Facility A	Facility B
Project size, kWdc	3,222.50	532.80
1 year energy production, kWh	4,076,515.00	595,434.00
Expected 1 year production required by facility, kWh	1,127,173.51	164,640.00

Both systems were offered based on 2 major commercial models: solar lease and power purchase agreement. Solar panels are fixed tilt.

4.2.5.1. Roof Lease Agreement

This approach considers that building owner provides the roof of facility for installation of solar project for supply of solar energy to a local community. Solar provider pays a rental cost to the building owner for a specific period of time. Considering a relatively small size of both projects, none of them make it possible both payments of rental to the building owner and connection to the project maintaining the rental payment from the solar provider. The benefit for the organization is the opportunity to offset the cost of grid electricity supply as well as provision of basis for green energy supply for the local community, thus only indirectly offsetting grid emissions of electricity supplied for warehousing operations. General overview of solar lease financial benefits from the solar provider is available in the Table 12.

Table 12

Overview of Solar Lease Financial Benefits

Parameter	Facility A	Facility B
Rent payment, annual	190,000	30,000
Lease term	20 years	20 years
Total aggregate benefit over the lease term	3,800,000	600,000

4.2.5.2. Power Purchase Agreement

With this approach, solar provider will use the roofs of both facilities for installing a solar project where the organization will be able to access the supply of clean energy generated from solar panels. As per provided proposal, there's a clear financial benefit (Table 13) from connecting to this project as cost of solar PPA is lower than current average utility cost for both facilities.

Table 13

Overview of Power Purchase Agreement Financial Benefits

Parameter	Facility A	Facility B
Current utility, USD/kWh	~0.17	~0.17
Solar PPA rate, USD/kWh	0.07	0.08
Annual rate escalator	1%	1%
Lease term	20 years	20 years
Max year 1 PPA savings, USD	112,717.35	53,588.16

Expected KPIs level for solution – power purchase agreement

Maersk is aiming at reaching a direct positive impact on Scope 2 emissions, therefore, we decided to prioritize the option of power purchase agreement as this approach provides a direct access to clean energy. Impact of implemented solution is expected as per Table 14:

Table 14

Overview of KPIs Results for PPA Implementation with Financial Benefits

KPI	Facility A	Facility B
Financial benefit, annual, USD	112,717.35	14,817.60
Environmental, saving annual, tones of CO2	333.61	48.73
Payback, years	0	0

Payback is 0 years due to the fact that there are no up-front cost for a building owner as they are absorbed by the service provider. The following additional benefits of the implementation of solar projects can be highlighted:

- Produce enough carbon-free electricity to power approximately 470 homes per year.
- Reduce wear and tear on the roofs.
- Eliminate upfront cost for a building owner.

Even though payback was defined as economical KPI we still decided to consider an additional financial KPI that was assessed as per the following formula:

$$FI = EC * \left(E_{grid} - E_{solar*}\right) + Tax * CO_2$$

Where:

FI – annual financial impact out of project implementation

EC – expected annual electricity consumption, kWh

E_{grid} – cost of electricity supply from grid

E_{solar} – cost of electricity supply from solar project

Tax – value of carbon tax

CO_2 – amount of CO_2 avoided due to implementation of project

Environmental impact was evaluated as per the following formula:

$$EI = EC * F_{grid}$$

Where:

EI – annual environmental impact out of project implementation

EC – expected annual electricity consumption, kWh

F_{grid} – grid factor relevant for the specific grid subregion of the US.

4.2.6. Way Forward

All the examined solutions necessitate that the building ownership be maintained in order to proceed with further steps in the project implementation process. In case of Maersk, the additional discussions with owners of warehouses are needed, unless Maersk owns a specific facility. This is considered as a severe limitation for this project. The project review and implementation stages at the level of each facility could be considered as follows:

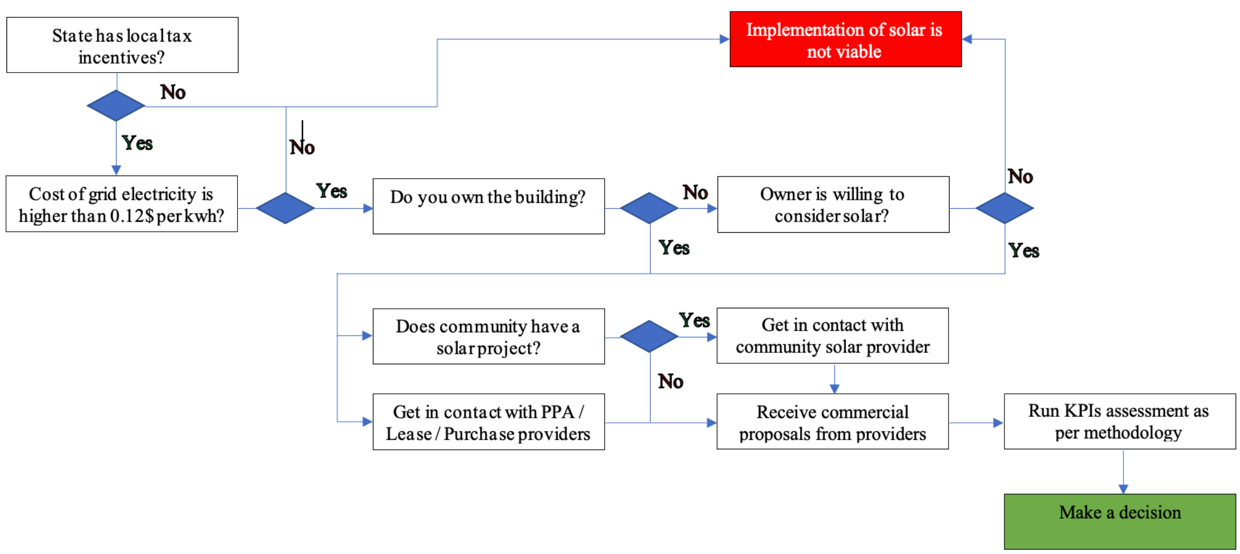
1. Solar project provider and building owner/Maersk agree on the site layouts and indicative cost of roof lease.
2. Solar project provider and building owner/Maersk execute Letter of Intent (LOI):
    a. Submit Interconnection Application to grid electricity provider – PSE&G.
    b. Execute Site Visit and Roof Structural Analysis.
    c. Submit to NJ Incentive Program.

3. Solar provider and building owner/Maersk execute the Power Purchase Agreement.
4. Solar project provider completes project development process, including permitting and finalizing submission to the NJ Community Solar Program.
5. Solar project provider builds and commissions the project(s).

In terms of project scalability to other geographies, the following steps must be undertaken to assess the attractiveness of solar as a solution as per Figure 11:

Figure 11

Roadmap of Solar Solution Scaling to Other Facilities



4.3. Wind Turbines

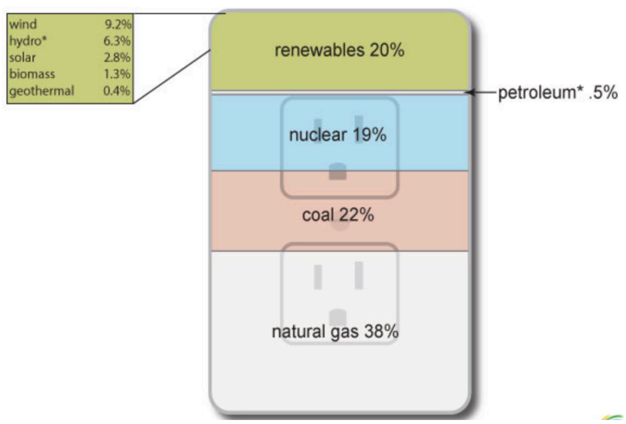
4.3.1. Introduction:

Wind turbines have been gaining popularity in the United States as an alternative clean energy source. Over the years, the country has made substantial progress in harvesting the power of wind to generate electricity. In the figure below from the U.S Energy Information Administration (EIA), wind energy represented the largest source of renewable electricity generation in the United States, making up 9.2% of the country's total electricity generation in 2021 (U.S. Energy Information Administration, 2018).

Due to the latest technological advancement in the wind energy generation sector along with the expected breakthroughs in the related technologies, the Office of Energy Efficiency & Renewable Energy in the US envisions the wind generated energy to represent 35% of the nation's electricity generation by 2050 (Department of Energy, 2021).

Figure 12

Renewable Energy Generation Method Share in the US



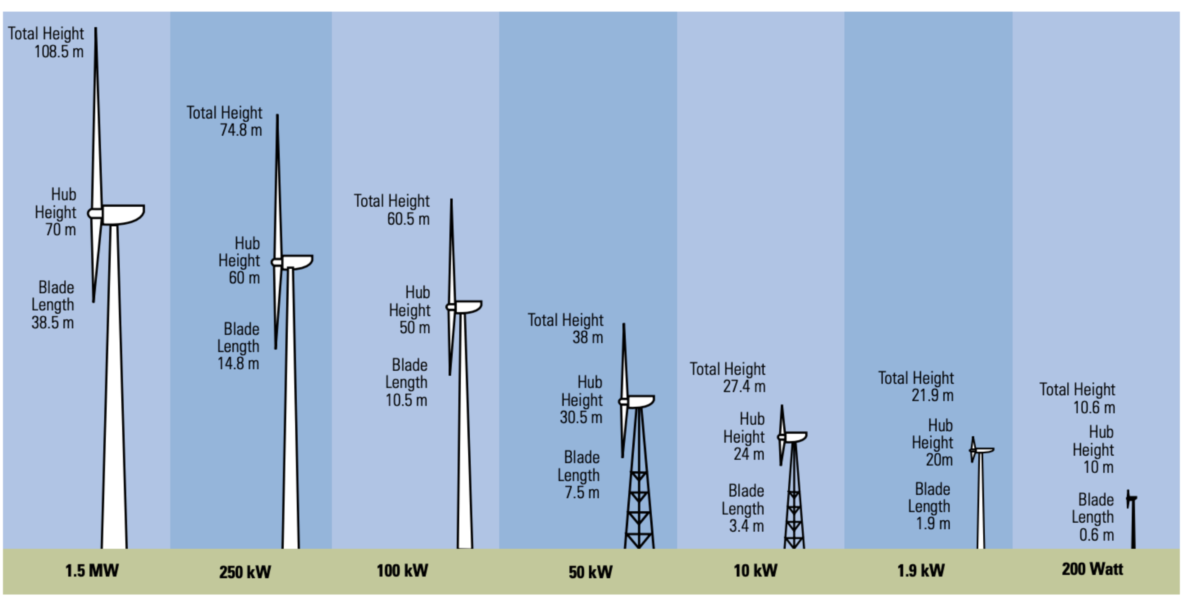
Source: U.S. Energy Information Administration. (n.d.). *Electricity in the U.S. Energy* Explained. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

4.3.2. Solution Overview

Aside from the large scale onshore and offshore wind energy generation projects, for the purpose of our research we focused on the available technologies that can be a good fit to generate energy off grid on site to support the warehouses match their electricity needs from sustainable sources. Wind turbines have been growing in size and height to capture more of the wind kinetic energy (Department of Energy, 2022b). The size of wind turbines installed in industrial buildings can vary depending on a variety of factors, including the available space, wind resource, and energy demand of the building. In general, wind turbines installed in industrial buildings tend to be smaller than those installed in utility-scale wind farms, but larger than those installed in residential or small commercial settings. Although there is no universally accepted definition of what constitutes a "small" wind turbine, small wind turbines typically have a rated capacity of up to 100 kW (Department of Energy, 2007). Figure 13 below shows the difference between the sizes and capacities of different wind turbines (Canadian Wind Energy Association, 2013).

Figure 13

Wind Turbines Size Comparison



Source: Canadian Wind Energy Association. (2013). *Small Wind Turbine Purchasing Guide: Off-grid, Residential, Farm & Small Business Applications.* https://web.archive.org/web/20130302211547

In our study, we focused on small wind turbines and compared between 3 different solutions that differ in their size, costs, and installations methods. We have selected 3 companies to work with and choose 3 different turbines to study aiming to capture all the possible wind energy generation strategies at the warehouse level.

15 kW turbine. This turbine is the biggest one in our study. With rotor diameter of 31.5 ft (9.6m), this turbine requires to have a dedicated tower on site to support its weight and to lift it to the optimum height. The turbine we analyze is Excel 15 that is present in Figure 14.

Figure 14

15 kW Turbine

Source: Bergey Windpower Co. (2022). *Excel 15: A Breakthrough in Small Wind Affordability. Bergey Windpower Co.* https://www.bergey.com/products/grid-tied-turbines/excel-15/

Specifications obtained from one of the providers:

- AWEA Rated Power: 15.6 kW at 11m/s (24.5 mph)
- AWEA Rated Sound Level 48.5 dB(A)

- Max Design Wind Speed: 60 m/s (134 mph)
- Type: 3 Blade Upward, Horizontal Axis
- Tower Height: 36.6 m (120 ft)

5 kW Turbine. The analyzed wind turbine in this project is developed by a company as an innovative, cutting-edge technology designed to harness the immense potential of wind energy in a more efficient and sustainable manner. As a state-of-the-art wind turbine, the company boasts several unique features that set it apart from traditional designs. Its aerodynamic blade structure not only maximizes energy capture but also minimizes noise pollution. The turbine has relatively small dimensions (84.8 x 108.9 x 174.5 Inches - 2155 x 2768 x 4433 mm) with a weight less than 0.5 Tn (1,000 lb) that makes it more mobile than the available big solutions.

Micro Turbine. The smallest turbine we chose for our analysis is the Air 40 that is developed by one of the providers. With 1.17 m (46 in) rotor diameter that is recommended to be mounted 10 m (33 ft) above the ground level as showing in Figure 15 (Department of Energy, 2022a). Those turbines can be a great solution for the leased locations. Technical specs obtained from a solution provider:

- Swept Area 1.07 m2 (11.5 ft2)
- Rotor Diameter 1.17 m (46 in)
- Weight 5.9 kg (13 lb)
- Startup Wind Speed: 3.13 m/s (7 mph)
- Voltage: 12, 24 and 48 VDC
- Survival Wind Speed: 40.2 m/s (90 mph)

Figure 15

Micro Wind Turbine

Source: Department of Energy. (2022a). *Small Wind Electric Systems*. https://www.energy.gov/energysaver/small-wind-electric-systems

4.3.3. Payback and Environmental Assessment: Methodology

The saving in GHG emissions coming from the wind turbines is related to the amount of energy they are able to generate on site. The formula to calculate the monthly generated electricity in kWh is simplified to be as follows (Thunder Said Energy, 2020):

$$Energy\ (kWh) = 0.5 * \rho * A * Cp * V^3 * 24 * 30 / 1000$$

Where:

ρ = density of air (in kg/m^3)

A = swept area of the turbine blades (in square meters)

Cp = coefficient of performance or power coefficient (typically between 0.25 and 0.45)

V = average wind speed (in meters per second)

24 = number of hours in a day

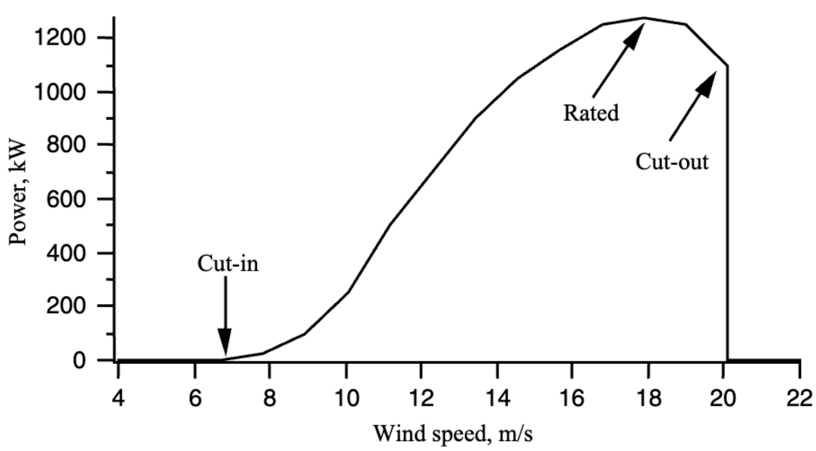
30 = number of days in a month

The challenge and complexity to calculate the output of this formula comes from 2 factors:

- The wind speed is usually reported with the average speed per day at a certain location while the actual wind speed that will be moving the blades of the turbine can generate energy that is different than the one of the formula. This is mainly due to the fact that the relationship between the energy generation and the wind speed in not linear as showing the in Figure 16 (Manwell et al., 2009). Moreover, the reported average wind speed does not account for the height of the wind turbine along with the surrounding obstacles that can slower the wind speed.

Figure 16

Typical Wind Turbine Power Curve



Source: Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2009). Wind Energy Explained: Theory, Design and Application (1st ed.). Wiley. https://doi.org/10.1002/9781119994367

- The coefficient of performance is highly related to a specific wind turbine as it's related to its mechanics, blade shape and orientation compared to the wind flux.

As a solution, the manufacturers usually develop datasheets for their products, in which the user can have an estimation of the generated energy based on energy output graphs adjusted for the efficiency factors. In our analysis we used those graphs, and at the same time, we asked the manufacturers to support us with wind assessment studies for simulation for having their respective products at a specific height in the warehouse locations.

From estimating the electricity generation of a wind turbine, we can estimate the added environmental value and the reduction of the GHG emissions through the following formula:

$$\boldsymbol{EI = \left(EG * GF_{electricity}\right)}$$

Where:

EI – expected annual environmental impact out of project implementation, CO2 tones

EG – expected annual electricity generation per year, kWh

$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh

Putting all the results together, we estimated the payback period for the investment by the following formula:

$$Payback = \frac{Initial\ Investment - Tax\ Reliefs}{Electricity\ Generation\ per\ Year * Electricity\ Rate}$$

4.3.4. Proposed Solutions for Selected Warehouses:

- **KPIs Assessment:**

In the analysis below, we show 2 payback periods, one is a result of having an estimated energy generation and the other is done by having a wind energy assessment for the selected sites. The purpose of having both is to show the difference between the approximate and quick method compared to the detailed simulation analysis that can be done for a specific location.

Tax reliefs being an important part of the equation currently sum up to 60% of the cost of the project:

- 30% Investment Tax Credit (ITC)
- 10% bonus credits apply to products meeting “domestic content” guidelines
- 10% credits if the project is in a designated “low-income community”
- 10% if the project is in a “brownfield” location, or a community with a recent coal plant or mine closure

In our analysis, we are only considering 40% tax relief as the assigned locations do not qualify for the remaining 20% of the bonus tax credit. Moreover, we considered the following:

- Facility A’s average annual wind speed: 10.8mph
- Facility B’s average annual wind speed: 10.2mph
- Electricity cost in Facility A: 0.17 USD per kwh

- Electricity cost in Facility B: 0.17 USD per kwh
- Grid factor (Facility A & Facility B): 0.6728 Tn/MWh
- No assessment was done for the 5 kW turbine solution in Facility B because the wind blows on the short side of the building, making it difficult to utilize the roof to install multiple units.
- There are no estimated electricity generation numbers for 5 kW turbine system because a datasheet is still not available.
- Number of wind turbines, shown in Table 15, are chosen to have all solutions having a similar capex to the one of 15 kW turbine to allow comparison despite the fact that the warehouses can accommodate to have more 5 kW or Micro turbines.

Table 15

Results of KPIs Assessment for Facility A and Facility B – Wind Turbines

	Turbine	Number of Turbines	Cost		Tax Relief	Electricity Generation		CO2e Savings		Payback Period	
			USD/Unit	USD	USD	Estimated kWh/Yr	Simulated kWh/Yr	Estimated Tn/Yr	Simulated Tn/Yr	Estimated Yrs	Simulated Yrs
Facility A	15 kW	1	125,000	125,000	50,000	28,000	25,000	8.55	7.64	9.96	11.15
	5 kW	10	12,000	120,000	48,000		70,000		21.38		3.82
	Micro	100	1,200	120,000	48,000	34,800	31,320	10.63	9.57	7.69	8.55
Facility B	15 kW	1	125,000	125,000	50,000	24,000	22,000	7	6.72	11.62	12.67
	Micro	100	1,200	120,000	48,000	28,800	25,920	8.80	7.92	9.29	10.33

- Required Permits. The permits required to install wind turbines in the United States typically involve a combination of federal, state, and local regulations. As there are no requirements for installing the smaller turbines types, there are two permits that are required for the bigger size turbines:

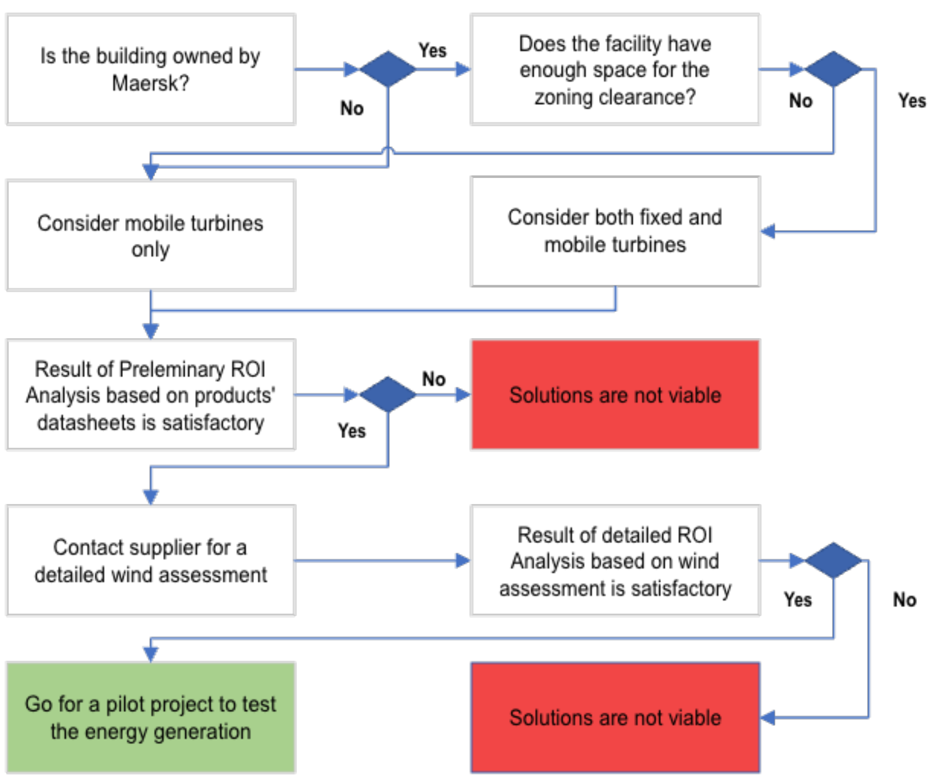
- State and Local Zoning and Land Use Approvals: These approvals ensure that the project aligns with local zoning ordinances and land-use plans. Also, in this permit, the clearance around the turbine is checked and approved. Usually, it's mandatory that the owner of the turbine own the land around it with a radio equal to 110% of the height of the tower (source).

- Federal Aviation Administration (FAA) Permit: Wind turbines that exceed a certain height may require a permit from the FAA to ensure compliance with aviation safety regulations. This is highly applicable to Facility B as it's close to Newark airport.
- Permitting & inspection requirements for construction projects in the US. Standard Electrical, Building & Fire and Life Safety Codes.

4.3.5. Way Forward

Figure 17

Roadmap for Scaling Wind Turbines Solution to Other Location



4.4. Yard Goats

4.4.1. Solution Overview

Yard goats also known as (yard tractors) are vehicles designed for the movement of containers on the territory of warehouse, depot, or a distribution center. Unlike other tractors, yard goats are very rarely used on roads and mostly used inside of a warehousing complex only. NACFE states that currently 90% of all yard goat sales are configured to off-road use (North American Council for Freight Efficiency, 2022b). Yard goats have some other unique features if comparing with other trucks, such as:

- A single-person cabin
- Full height rear sliding door allowing yard goats to be parked in tight areas
- Short wheelbase and low turning radius to ease the movement of vehicle in a Limited space area
- Low speed in average (14-29 mph)
- Low traveling distance per day

Table 16

Shares of Yard Goat Market in the USA and Canada

Manufacturer	Approx. US and Canadian share	Manufacturing plant location
Kalmar/Ottawa	40%	Kansas City, MO
Capacity	25%	Longview, TX
Tico	15%	Ridgeland, SC
Autocar	10%	Hagerstown, IN
Orange	10%	Riverside, MO; Texarnaka, TX

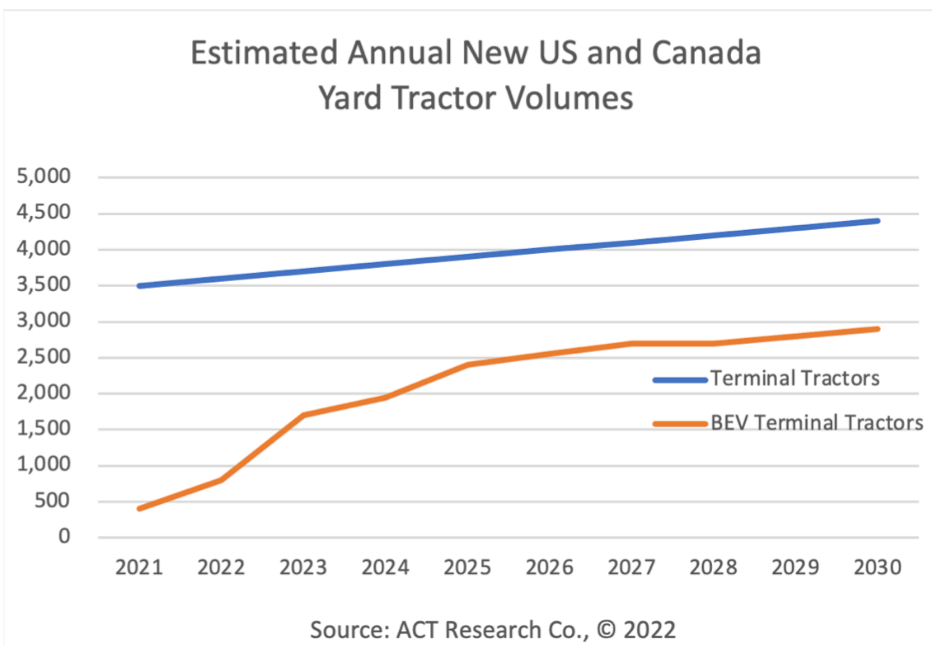
Source: NACFE. (2022). *Terminal Tractors: Market Segment and Fleet Profile.* https://nacfe.org/wp-content/uploads/2022/01/Terminal-Tractors-RoL-E-Fact-Sheet.pdf

The market size of yard goats is relatively small in North America: it was estimated to be around 50K units being operated on 2022 (North American Council for Freight Efficiency, 2022a). There are only 5 major manufacturers that dominate the market and deliver approximately 2.5K units annually to the North American Market.

Nevertheless, it is expected that the yard goats' market will grow from 700M USD in 2021 to more than 500M USD in 2026. North American Council for Freight Efficiency claims that if all fleet of yard goats in the USA and Canada was electrified, it would save approximately 929,687 MT CO2 annually (North American Council for Freight Efficiency, 2022a).

Figure 18

Estimated Annual New US and Canada Yard Goat Sales Volume



Same as for traditional trucks, tendency of electrification also reached yard goats. Figure 18 represents the expected annual value of sales of new yard goats in the US and Canada, as well as the portion of those that are electrified.

Starting late 2010s, on-site yard goats were required to meet Tier 4 off-highway emissions regulations (CK Power, 2015). Mentioned regulation pushed owners of diesel driven vehicles to install diesel particulate filters (DPF) and selective catalytic reduction. The exhaust system rarely reaches the temperatures required for proper DPF regeneration to occur, making the usual duty cycle for a terminal tractor rather difficult for these aftertreatment components. Companies have reported that they have been experiencing high rate of replacement of mentioned parts, thus, DPF repair cost can vary between 2,500 and 8,000 USD – it depends on whether the installed unit is newly manufactured or a refurbished one. As a result, the maintenance cost for diesel yard goats significantly increased within the last few years. At the same time, some of fleets stated that expected life of diesel terminal tractors would be reduced as expected from 12 years to 10 years (North American Council for Freight Efficiency, 2022a).

Together with increased maintenance costs for diesel yard goats, the following claimed benefits result in increasing the amount of sale of electrical yard terminal tractors:

- Lower cost of electricity vs diesel (subject to the conditions of the local market).
- Claimed lower maintenance vs diesel engines.
- Emissions footprint is smaller.
- No odors when operating.

- Possible avoidance of licensing fees (applicable for diesel powered vehicles in certain areas).
- Possibility to operate inside the warehouse (due to the absence of emissions on-site).
- Considered as a good option to understand which real TCO components and considerations must be taken into account for the further extension of electric vehicles fleet.

Nevertheless, there are some challenges associated with operation of electric terminal tractors:

- Higher purchase price vs diesel driven vehicles.
- Cost of charging infrastructure and batteries.
- Need for extra trainings for drivers, technicians.

Important trend to be considered is the advancement of the automation of yard goats. Several companies including startups such as Outrider are currently developing and testing electrical yard goats that are able to perform the work without a driver (North American Council for Freight Efficiency, 2022b). Lower driving speed is the key factor that helps to run this process easily.

4.4.2. Electric Vehicles vs Diesel Driven: Factors of Attractiveness

Cost of purchase of electric yard goats varies between 275K USD and 350K USD vs 100K-120K USD for diesel driven vehicles. If comparing the economical attractiveness of electrical vehicles only based on the purchasing cost, it is obvious they are not the best option. However, the correct assessment approach should be based on total cost of ownership.

When accounting only for the purchase price, fuel savings and maintenance cost savings (claimed to be 60-75% lower vs diesel vehicles), the payback period for an electric yard goat can be around 8 years. In fact, the main driver for the payback assessment of electrified yard goats is the cost of electricity in the warehouse.

4.4.3. Challenges and Specific Considerations

While considering the implementation of yard goats, a company needs to consider some applicable potential challenges.

Battery parameters: a company needs to confirm battery size and range with each manufacturer. It is also important to take into account number of other factors such as: the KW rating of the onboard AC charger, the DC connector type (CCS), the system operating voltage (400V or 800V), the maximum DC charge rate, the vehicle's ability to receive over-the-air software and firmware updates, and communication capabilities. This allows the ability to monitor the battery pack's condition and report charge event data.

Charging: Electric vehicles typically take a significant time to get fully charged, which is in contrast to diesel vehicles that can be refueled in just a few minutes. This difference may require introducing operational and yard layout changes to account for the required charging time. Table 17 below provides some insights on the charging cycle of a 120kWh battery based on charger power level (North American Council for Freight Efficiency, 2022a):

Table 17

Approximate Charting Time for a Battery Electric Yard Goat

Low power (220V single phase AC – 7kW)	Medium power (19.2 kW)	480 3-phase AC or DC (40 kW)	DC Fast Charging (150 kW)
17+ hours	6.25 hours	3 hours	1 hour

Idle time: As cost of a charging station goes up, so does the price, therefore it is worth making a better use out of idle time to opportunity charge as it would help to reduce infrastructure cost due to the smaller amount of chargers needed. Luckily, yard goats typically have a high idle time (30% at least), for example, during pickup and drop activities. In some cases, truck's engine is left running when the truck is not moving containers just to maintain the environment inside of the cabin. This idle time can be used for the purpose of opportunity charging. For that reason, many adopters of electrified solutions plan their layouts with fast chargers located closer to the tractors' waiting zones.

Fuel consumption: The consumption of diesel by the current fleet of yard goats can pre-define the required capacity of a vehicle's battery and therefore, the cost of the vehicle. For instance, a typical terminal tractor would consume around 15 gallons of fuel daily if it ran 60 miles per day (at a consumption rate of 4 miles per gallon). On the other hand, an electric version of that tractor might utilize 2.5 kWh/mile. Hence, it would consume 150 kWh per day for the same daily mileage. To perform the same tasks as the diesel-powered truck version, the battery pack size for the electric tractor would need to be at least 225 kWh.

Off-time: Charging cycle can be adjusted considering off time. Understanding it is critical as truck can be plugged to charger relatively quickly and extra charging cycle can reduce the probability of equipment shortage during overtime operations.

On-road capability: Is there a need to use the truck on road? Some of the models are certified for a specific application off-road only.

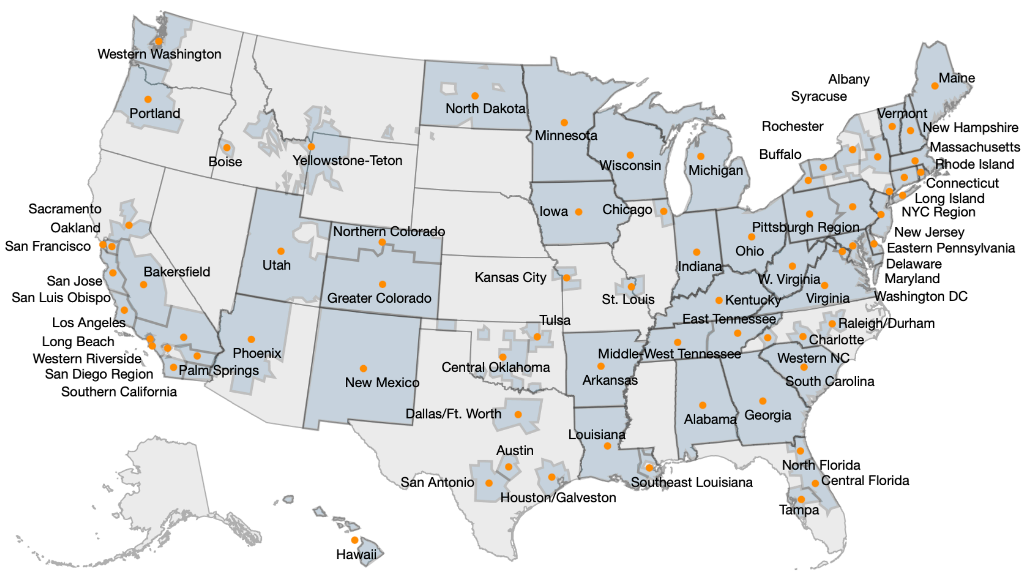
Capacity of unit: Electrified units typically have lower towing capacity if compared to the diesel-powered version.

The need to be used in overtime hours: Considering that the electrified yard goats need to be charged at the end of the last shift, the organization needs to consider the frequency of their need to work overtime to ensure that the charging cycle won't impact operations.

Incentives: are an important factor to be considered when studying the payback of introducing electric yard goats. A great source of available incentives is the U.S. Department of Energy's (DOE), Vehicle Technologies Office (VTO), and Clean Cities Coalitions (Figure 19). VTO creates collaborations at a national level and offers technical support, information resources, online tools, and statistics. At a federal level, VTO establishes partnerships and organizes technical assistance and analysis, information resources, and online tools and data. At the local level, coalitions leverage these resources to create networks of local stakeholders and provide technical assistance to fleets implementing alternative and renewable sources of energy, idle-reduction measures, fuel economy improvements, and emerging transportation technologies.

Figure 19

Map of Regions with Local Incentives in the United States



Source: Electrification Coalition. (2021). *Incentives.* https://electrificationcoalition.org/incentives/

There are several incentives provided by DOE, including:

- Joint Office of Energy and Transportation Notice of Intent for 2023 Ride and Drive Electric Research and Development Program Funding
- U.S. Department of Energy Notice of Intent for 2023 Advanced Vehicle Technologies Funding

Clean cities and their local representatives can help the organization to apply for relevant incentives. Other funding opportunities are provided by U.S. Department of Transportation and EPA. Inflation Reduction Act will also impact electric tractors, including yard goats. The credit is up to 7,500 USD for vehicles under 14,000 pounds and up to 40,000 USD for all other vehicles. Only certain vehicles are eligible for the credit, as the new law stipulates certain manufacturing and final assembly requirements (Electrification Coalition, 2022).

4.4.4. Payback and Environmental Assessment: Methodology

Payback assessment: despite the fact the price for electric yard goat is significantly higher in comparison to the diesel driven versions, it is important to consider the benefits that electrified vehicles bring to the organization. The following inputs are needed for a comprehensive payback assessment:

1. Vehicle purchase price.
2. Current fuel consumption of a yard goat.
3. Cost of electricity at the property.
4. Maintenance costs for both diesel and electric vehicles.
5. Available incentives,
6. Cost of charging infrastructure.

Based on results of review of different information sources as well as discussions with providers of electric vehicles, we could identify 2 approaches for calculating the payback for shifting to electrified vehicles:

1. Simplified – considering fewer factors for the payback calculations.
2. Advanced – covering wider range of factors for the payback analysis.

Both approaches require to use annualized data per 1 vehicle.

Simplified payback assessment approach. The main advantage of this approach is that it simplifies the analysis by running the payback assessment considering lower number of cost drivers. However, some important cost drivers, that can positively impact the payback, may be missing from this approach which can be disadvantageous to our analysis.

$$Payback = \left(\frac{EVC - DVC}{(S_{fuel+DEF} + S_{maintenance} + S_{CT}}\right)$$

Where:

Payback – expected payback electric yard goat

EVC – cost of electric yard goat, USD

DVC – cost of diesel yard goat, USD

$\mathrm{S}_{\mathrm{fuel+DEF}}$ – expected savings based on fuel and DEF consumption, USD

$S_{maintenance}$ – expected savings based on maintenance of vehicle, USD

S_{TC} – avoided carbon tax thanks to implementation of electric vehicle

Some components of mentioned formula need to be calculated as per the following:

Cost of electrical yard goat:

$$EVC = Truck + Infrastructure + Taxes + Charging\ Solution - Incentive$$

Where:

Truck – expected purchasing price of 1 electric yard goat, USD

Infrastructure - One-time electrical infrastructure cost equally allocated over all vehicles ordered, USD

Taxes - Tax dollars due based on tax rate applied to all EV cost elements, USD

Charging solution - Cost of charging solution per vehicle ordered, USD

Incentive - Total value of grants, vouchers, and tax credits that lower purchase price (or in effect act as a one-time benefit), USD

Expected savings based on fuel and DEF consumption:

$$S_{fuel+DEF} = EH * DU * DC + EH * DU * DEFU * DEFC - EH * EU * EC$$

Where:

$S_{fuel+DEF}$ – expected savings based on fuel and DEF consumption, USD

EH – engine hours, hours

DU – diesel use, gallons per hour

DC – diesel cost, USD per gallon

DEFU – DEF use rate, gallons of DEF per gallon of diesel

DEFC – DEF cost, USD per gallon

EU – electricity use, kwh per hour

EC – electricity cost, USD per kwh

Avoided carbon tax thanks to implementation of electric vehicle:

$$S_{tc=}\left(FC * EF_{fuel} - EC * GF_{electricity}\right) * Tax$$

Where:

FC – registered annual fuel consumption of 1 diesel vehicle, USG

EF_{fuel} – emissions factor for fuel consumption, CO2 per USG

EC – expected annual electricity consumption for 1 vehicle based on registered fuel consumption, kWh

$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh

Tax – value of carbon tax, USD per ton of CO2

<u>Advanced payback assessment approach.</u> The formula provided below helps to account wider range of costs and other factors affecting the total cost of ownership of electric vehicle. We recommend using this approach when more data is available at a specific warehouse level as it helps to achieve more accurate results as the model considers more cost components. At the same time, a company needs to make sure that all inputs for additional cost factors are reliable, otherwise the model will provide an overoptimistic result:

$$Payback = \left(\frac{EVC - DVC}{(S_{fuel+DEF} + S_{maintenance} + S_{ec} + S_{oc} + S_{CT}}\right)$$

Where:

Payback – expected payback of electric yard goat

EVC – cost of electric yard goat, must cover:

- Charging infrastructure

- Cost of battery

DVC – cost of diesel yard goat

$S_{\text{fuel+DEF}}$ – expected savings based on fuel and DEF consumption, USD

$S_{maintenance}$ – expected savings based on maintenance of vehicle, USD

S_{ec} – expected savings based on emission control: incremental cost of the lost time associated with required regen / high idle and downtime while diesel truck is out of service for repair

S_{oc} – expected savings based on other cost components

S_{TC} – avoided carbon tax thanks to implementation of electric vehicle

Some components of mentioned formula need to be calculated as per the following:

Cost of electrical yard goat:

$$EVC = Truck + Infrastructure + Taxes + Charging\ Solution - Incentive$$

Where:

Truck – expected purchasing price of 1 electric yard goat

Infrastructure - One-time electrical infrastructure cost allocated over all vehicles ordered.

Taxes - Tax dollars due based on tax rate applied to all EV cost elements

Charging solution - Cost of charging solution per vehicle ordered

Incentive - Total value of grants, vouchers, and tax credits that lower purchase price (or in effect act as a one-time benefit)

Expected savings based on fuel and DEF consumption:

$$S_{fuel+DEF} = EH * DU * DC + EH * DU * DEFU * DEFC - EH * (1 - IT) * \frac{EU}{CE} * EC$$

Where:

$S_{fuel+DEF}$ – expected savings based on fuel and DEF consumption, USD

EH – engine hours, hours

DU – diesel use, gallons per hour

DC – diesel cost, USD per gallon

DEFU – DEF use rate, gallons of DEF per gallon of diesel

DEFC – DEF cost, USD per gallon

IT – idle time, %

EU – electricity use, kwh per hour

CE – charging efficiency, %

EC – electricity cost, USD per kwh

Expected savings based on maintenance of vehicle:

$$S_{maintenance} = EH * M\&RC_{diesel} - EH * (1 - IT) * M\&RC_{electric}$$

Where:

$S_{maintenance}$ – expected savings based on maintenance of vehicle, USD

EH – engine hours

$M\&RC_{diesel}$ – maintenance and repair cost of diesel engine, USD per hour of operation

IT – idle time, %

$M\&RC_{electric}$ – maintenance and repair cost of electrical engine, USD per hour of operation

Expected savings based on other cost components:

$$S_{oc} = DT + FMC + EMC + HMC + Tire + OC$$

Where:

DT – Reduced downtime: dollars Saved due to reduced downtime. This includes lost efficiency, lost profits, and direct cost of renting backup/emergency truck

FMC – Fuel management cost: eliminate diesel tanks, fuel shrinkage and diesel related fuel management costs.

EMC – Emission control cost – lost productivity: Incremental cost of the lost time associated with required regen / high idle and downtime while truck is out of service for repair

HMC – Hazardous material management cost: sites have to manage their hazmat programs as well as pay for spill-cleanup. Some sites are required to clean their lots of spill residue/stains at significant cost.

Tire - EV trucks can prevent dragging trailers which leads to replacing 6 flattened tires. Drivers also can't skid out so will in other ways save on tread wear.

OC – other costs applicable to a specific warehouse and operations there

Avoided carbon tax thanks to implementation of electric vehicle:

$$S_{tc} = \left(FC * EF_{fuel} - EC * GF_{electricity}\right) * Tax$$

Where:

FC – registered annual fuel consumption of 1 diesel vehicle, USG

EF_{fuel} – emissions factor for fuel consumption, CO2 per USG

EC – expected annual electricity consumption for 1 vehicle based on registered fuel consumption, kWh

$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh

Tax – value of carbon tax, USD per ton of CO2

Environmental impact assessment. For the case of Maersk, we consider electrified yard goats to replace diesel driven yard goats. In this case calculation of environmental impact goes directly from the difference of emissions from diesel vehicles and electric ones. The most accurate method for emissions calculation is fuel based.

$$EI = \left(FC * EF_{fuel} - EC * GF_{electricity}\right) * N$$

Where:

EI – expected annual environmental impact out of project implementation, CO2 tones

FC – registered annual fuel consumption of 1 diesel vehicle, USG

EF_{fuel} – emissions factor for fuel consumption, CO2 per USG

EC – expected annual electricity consumption for 1 vehicle based on registered fuel consumption, kWh

$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh

N– number of vehicles in the fleet of warehouse

4.4.5. Proposed Solutions for Selected Warehouses – KPIs Assessment

To assess potential outcome of electrified yard goats' implementation at the level of Facility A and Facility B, we contacted one of the key players of electric yard goats' market. We were able to obtain the preliminary commercial proposal from them as well as some insights on the cost drivers of their solution. Combined, based on this information as well as data obtained from Facility A and Facility B warehouse managers, we calculated payback based on 2 mentioned approaches with inputs presented in Table 18.

Table 18

Inputs of Parameters for a Payback Assessment and Their Sources

Parameter	Value	Source
EVC – cost of electric yard goat, USD	285,565.00	Estimated price from yard goats provider
DVCC - cost of diesel yard goat, USD	154,565.00	Estimated price from yard goats provider
EH – engine hours, hours	2.250.00	Provided by warehouse managers
DU – diesel use, gallons per hour	0.92	EH / Recorded fuel consumption
DC – diesel cost, USD per gallon	4.814	(American Automobile Association, 2023)
DEFU – DEF use rate, gallons of DEF per gallon of diesel	0.92	EH/FC
DEFC – DEF cost, USD per gallon	0.13	(EnergySage, 2023)
EU – electricity use, kwh per hour	12	Specs of yard goats provided by manufacturer
CE – charging efficiency, %	91%	(Kuhn et al., 2005)
EC – cost of electricity, USD per gallon	0.17	(U.S. Energy Information Administration, 2023b) Bills provided by warehouse managers
$M\&RC_{diesel}$ – maintenance and repair cost of diesel engine, USD per hour of operation	9.86	Estimates provided by yard goats manufacturer
$M\&RC_{electric}$ – maintenance and repair cost of electrical engine, USD per hour of operation	2.57	Estimates provided by yard goats manufacturer

Parameter	Value	Source
IT – idle time, %	30%	(North American Council for Freight Efficiency, 2022b)
$S_{maintenance}$ – expected savings based on maintenance of vehicle, USD	~8,000.00	(North American Council for Freight Efficiency, 2022b)
FC – registered annual fuel consumption of 1 diesel vehicle, USG	2,080.00	Information provided by warehouse managers
EF_{fuel} – emissions factor for fuel consumption, CO2 per USG	10.21	(U.S. Energy Information Administration, 2023a)
EC – expected annual electricity consumption for 1 vehicle based on registered fuel consumption, kWh	27,000.00	EH*EU
$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh	0.6728	(EPA, 2021)
Tax – value of carbon tax, USD per ton of CO2	75	Provided by Maersk

All the cost that contribute to the group of other cost components must be estimated by site managers directly considering specifics of the local operations.

Table 19

Results of Payback Assessment for Facility A and Facility B

Approach	Facility A, years	Facility B, years
Simplified	8.91	8.27
Advanced, yard goat manufacturer's data	4.10	3.70
Advanced, MIT data	6.60	5.00

Following the formula for environmental impact assessment, we have the following volumes of tons of CO2 avoided per calendar year as per Table 20.

Table 20

Tons of CO2 Avoided in Each Warehouse

Facility	Saving of CO2, tons per year, per vehicle	Number of vehicles	Total saving of CO2, tons per year
Facility A	8.24	2	26.00
Facility B	27.69	9	249.18

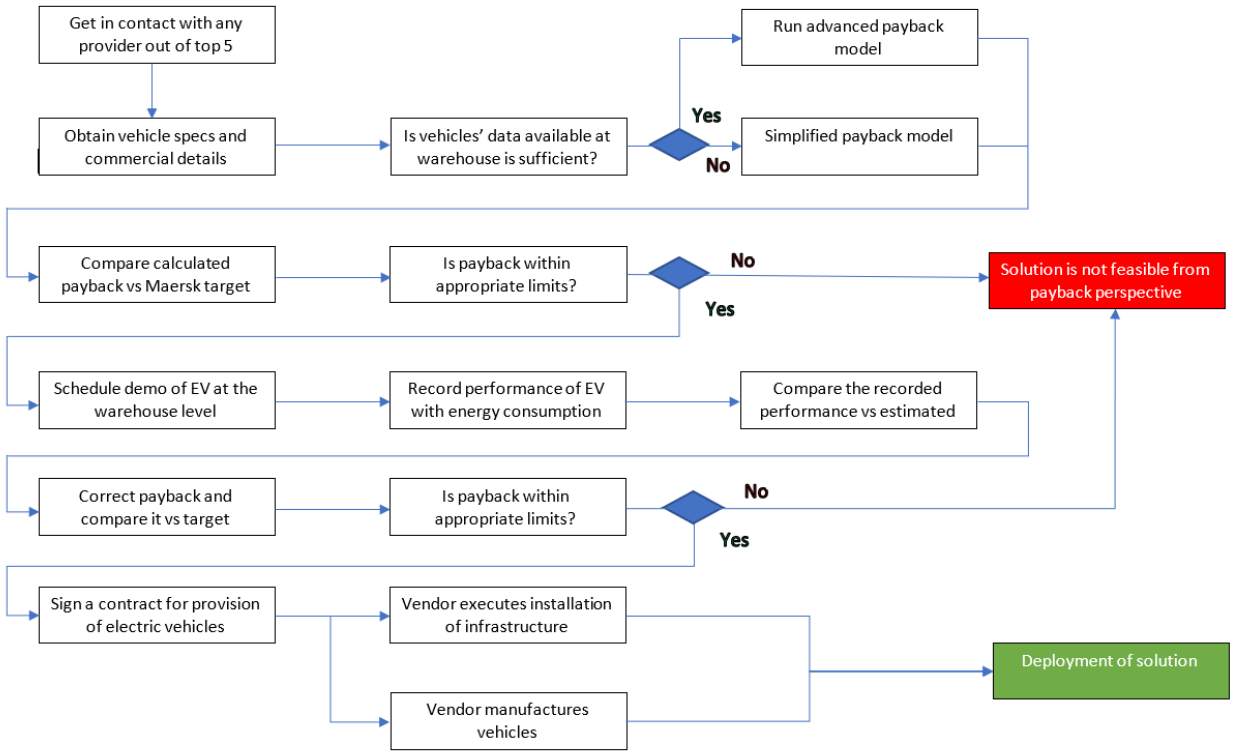
4.4.6. Way Forward

Despite the fact the essence of operations do not differ a lot between warehouses of the same type (transshipment and fulfillment), still the intensity of operations can be different which will affect the payback assessment. Thus, as per provided methodology, payback is a function of fuel consumption as well: the higher consumption – the better payback (due to the impact of cost difference between electricity supply and diesel).

For that reason we provide the roadmap for assessment of scalability of solution for a specific warehouse as per Figure 20.

Figure 20

Roadmap for Scaling Electric Yard Goats to Other Facilities



4.5. HVLS Fans

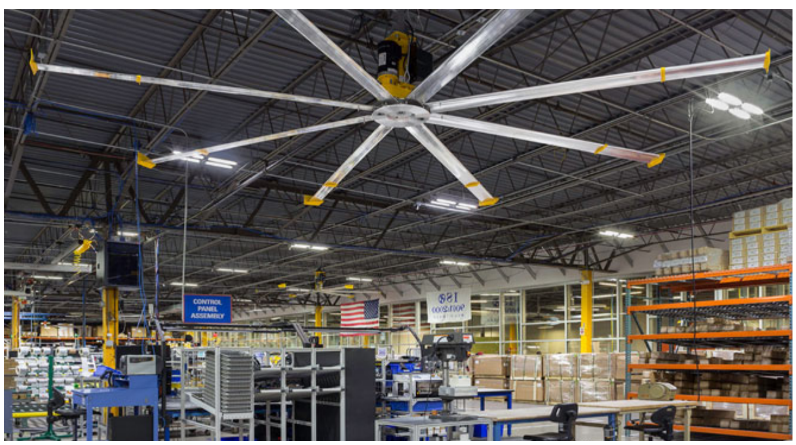
As a Heating, Ventilation, And Air Conditioning (HVAC) system gets the lion share of the energy in a temperature-controlled warehouse (Ries et al., 2016), we have explored the high-volume low speed (HVLS) fans as an emerging technology that would work with the HVAC system to maintain the desired temperatures at a lower energy consumption rate. Despite the fact that warehouses are typically not temperature-controlled, we believe that implementing HVLS fans can decrease the heat stress experienced by workers during hot summer days leading to a higher employee wellbeing. Thus, NASA discovered that in a business setting, a temperature increase of 5 degrees, from 80 to 85 degrees, leads to a decrease of 18% in employee productivity and a 40% decrease in the accuracy of their work. To cool these vast areas, HVLS fans are the most efficient and effective option (Watson, 2022).

4.5.1. Solution Overview

HVLS (High Volume, Low Speed) fans are a type of ceiling fan with a diameter of more than 7 feet and a blade speed of less than 100 revolutions per minute. These fans are designed to move large volumes of air at low speeds, typically in industrial and commercial spaces with high ceilings as showing in the picture below (Cisco-Eagle, 2020).

Figure 21

Typical HVLS Fan



Source: Cisco-Eagle. (2020). *Justifying HVLS Big Ass Fans.* https://www.cisco-eagle.com/category/3157/justifying-a-high-volume-low-speed-fan

HVLS fans were introduced as an alternative to traditional fans. Using High Volume Low Speed (HVLS) fans requires only a few units to cover a large area, whereas traditional fans require many units. Thus, for a 9000 sq. meter area, only 6 HVLS fans are needed, while nearly 300 traditional fans would be required to cover the same area (RT Fans, 2019).

Thanks to their long blades, the fans, with minimum energy, can move a large volume of air wile rotating at a low speed. In summer, the air circulation create a breeze that can reduce the perceived temperature by up to 10 to 12 degrees Fahrenheit (Action Lift, 2020). In winter the hot air tends to raise and start accumulating at the ceiling due to its lower density comparing to cold air. Having an installed HVLS fan allows the cumulated warm air at the top of the warehouse (in case of having a heating system installed) be pushed down to be around the warehouse workers. During the cold days, fans are set to run continuously at a speed of 20% to 30% of their maximum RPM to facilitate air mixing within a space without creating any noticeable drafts.

HVLS fans are a promising technology for improving energy efficiency, indoor air quality, and thermal comfort in industrial, commercial, and healthcare settings. Several studies have demonstrated the effectiveness of HVLS fans in achieving these goals, highlighting the potential for wider adoption of this technology in the future.

High efficiency of HVLS fan depends on several factors. A company needs to consider them when installing the system (Refresh Fans, 2021):

- Disregarding coverage area requirements: Not calculating the desired airflow coverage area before installation can result in improper cooling and heating performance from the HVLS fan.
- Improper distance between floor and fan: HVLS fans require sufficient clearance from the floor to provide effective indoor air temperature. Installing

the fan too low can result in inadequate performance, while installing it too high may require the use of a downrod.

- Disregarding the condition and capacity of the mounting structure: It is important to analyze the structural capacity, stability, load-bearing capacity, and limitations of the structure where the fan will be mounted. A structural engineer can review and affirm the strength and stability of the structure before mounting the ceiling fan.
- Neglecting electrical specifications: Determining voltage requirements is a fundamental prerequisite that should not be neglected. If the product exceeds the voltage specifications or capacity of the firm, it will not work.
- Neglecting the significance of wiring: The system of wiring is important for integrating the HVLS fan into either an existing Building Management System or other HVLS fans. Neglecting or ignoring the wiring system may result in compromising long-term convenience.

4.5.2. Limitations

The main limitations of using HVLS fans are related to the dimensions and the configuration of the warehouse.

- Blade Clearance:
  - ≥ 2 ft from objects
  - ≥ 3 ft below sprinkler head
  - To wall ≥ diameter * 0.5
  - ≥ 2.5 * diameter center to center
  - To ceiling ≥ diameter / 4 + 2 ft

- Blade Height
    - 10 ft above floor
    - ≥ diameter x 0.75

Moreover, studies have shown that HVLS fans can pose fire hazards by delaying the activation and impeding the operation of automatic fire sprinkler systems, causing uncontrolled fire spread and severe damage. The 2013 edition of NFPA 13 has issued set of standards to regulate the use of HVLS fans in sprinkled storage occupancies (National Fire Protection Association, 2013). HVLS fans can also contribute to spreading a fire in a warehouse by aiding a potential ignition with a soft air circulation. Therefore, HVLS producers have developed a system that would stop the fans in case of a fire. We believe that this system is mandatory to be installed in conjunction to the HVLS fans.

4.5.3. Assessment Methodology

Assessing the environmental impact of installing HVLS fans in a warehouse is highly dependent on many factors. The warehouse layout, roof height and racking system distribution are all factors that need to be taken into account when calculating the estimated effect of the fans. Big HVLS suppliers use simulation softwares that would model the air circulation in a warehouse along with its temperature in conjunction to the existing HVAC system. Only with those studies, an accurate estimate about the benefit of installing the HVLS fans can be obtained which leads to the saving in energy and CO2 emissions accordingly. The energy saving that can be generated from adding HVLS fans to the facility will be coming from the lower needed electricity for air conditioning in the summer and the lower natural gas consumption needed for heating in the winter. The thermal analysis and simulation that can be done by the supplier can provide both numbers which can be converted to CO2 emissions using the following formula:

$$EI = \left(GS * EF_{gas} + ES * GF_{electricity} - EC * GF_{electricity}\right)$$

Where:

EI – expected annual environmental impact out of project implementation, CO2 tones per year

GS – annual natural gas saving during winter, MCF per year

EF_{gas} – emissions factor for natural gas consumption, CO2 per MCF

EC – expected annual electricity consumption of HVLS, kWh

ES – expected annual electricity saving during summer, kWh

$GF_{electricity}$ – grid factor of CO2 pollution for a specific grid region of the United States, CO2 per kwh

With that, the payback period of the project can be calculated as follows

$$Payback = \left(\frac{CAPEX}{GS * GP + ES * EP + EI * CT - EC * EP}\right)$$

Where:

EI – expected annual environmental impact out of project implementation, CO2 tones per year

GS – annual natural gas saving during winter, MCF per year

GP – natural gas cost, USD per MCF

EC – expected annual electricity consumption of HVLS, kWh

ES – expected annual electricity saving during summer, kWh

EP – electricity cost, USD per kWh

CT – carbon tax, USD per ton

4.5.4. Assessment for Selected Warehouses

After analyzing the possibility to install HVLS fans in the assigned warehouses, we realized that:

- The Facility B warehouse is not suitable for HVLS fans due to having its ceiling lower than the required limit.
- The Facility A warehouse splits into 2 sections:
  - Section A (majority of the area): having a very high ceiling which was dropped down using a drop-down ceiling to get the sprinklers closer to the warehousing space. This drop-down ceiling cannot withstand the load coming from the fans.
  - Section B (smaller part of the warehouse): has a good height that would make it a good candidate for the solution. However, the warehouse already procured HVLS fans and had them installed prior to our study.

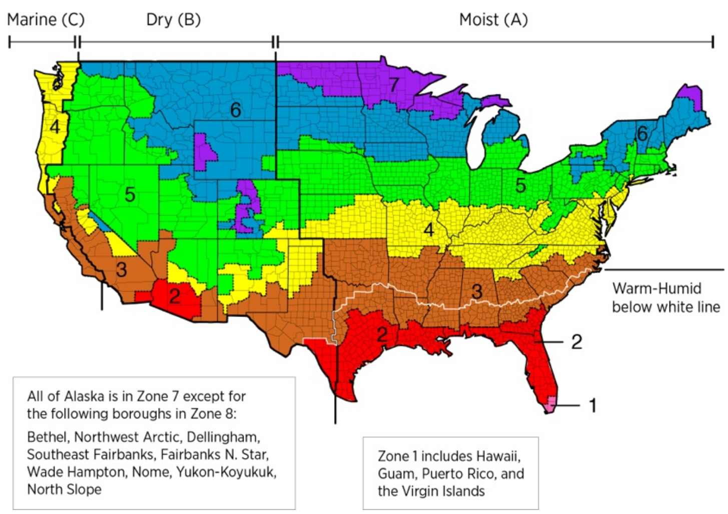
Due to the reasons above, we decided to ask our supporting organization to run the analysis on 2 warehouses with similar configurations in different locations for the purpose of our study.

- Location 1: 300,000 Square Foot assuming a location in Zone 2A (Savannah, GA).
- Location 2: 33,000 Square Foot assuming a location in Zone 5A (Chicago, IL).

The Figure 22 highlights the different climate zones in the US (Department of Energy, 2019).

Figure 22

Climate Zones Distribution in the United States



Source: ICC. (2020). *IECC climate zone map*. https://basc.pnnl.gov/images/iecc-climate-zone-map

Payback Assessment. When conducting a payback assessment for HVLS fans, it is important to consider all of the cost drivers that may be applicable to the specific case at hand. These cost drivers can vary depending on the particular situation, but typically include the following:

- Fan costs: depending on the fan type, ranges between 7,000 USD and 12,000 USD.

- Controllers: standard at no cost – ~600 USD for multi fan controller (up to 8).
- Fire safety sensor: ~500 USD for the first fan + 150 USD/additional fan.
- Installation: depends on the structure of the warehouse.
- Maintenance: N/A as the fans do not require a mandatory maintenance.
- Operation costs: depend on the zone and working times of the fans.

After analyzing the needed number of fans for both locations, the recommended number by the fans' company was 10 fans for location 1 and 5 fans for location 2. This leads the cost of the project to be:

- ~120,000 USD for Location 1 (10 Fans).
- ~61,000 USD for Location 2 (5 Fans).

The savings for this solution were calculated based on a thermal model for the warehouses considering 2 scenarios, with and without the fans/

The following assumptions were used while building a thermal model:

- HVLS fans AC energy saving is caused by air circulation that would allow the users to increase the thermostat set temperature without sacrificing the cooling comfort resulting in ~15% savings as per the EPA & DOE Energy Savings Calculator.
- Heating saving is caused by having the HVLS fans pushing the heated air to the workers levels which reduced the run time of the heating system.

All provided above assumptions and cost inputs led to the following model of the relevant impact assessment:

Table 21

CO2e Saving Result – HVLS

WH	Location	AC Electricity Savings	AC Electricity Consumption	Net Electricity Saving	Heating Energy Savings	Grid Factor	CO2e Saving
		kWh/Yr	kWh/Yr	kWh/Yr	MCF/Yr	Tn/kWh	Tn/Yr
1	Savannah(GA)	212,664	18,486	194,178	518	0.0004	107.11
2	Chicago(IL)	20,484	9,283	11,201	314	0.0005	22.62

Table 22

Results of Payback Assessment for Both Locations

	CAPEX	**AC saving**	**Heating Saving**	**Fans OPEX**	**CO2e Saving**		**Payback**
	USD	**USD/Yr**	**USD/Yr**	**USD/Yr**	**Tn/Yr**	**USD/Yr**	**Yr**
Location 1	120,000	19,948	4,105	1,734	107.1	8,033	4
Location 2	61,000	1,743	2,239	790	22.6	1,697	12

Based on the results of the thermal assessment done by the supplier for the selected locations, we summarize the environmental impact in Table 21 and economical impact in Table 22.

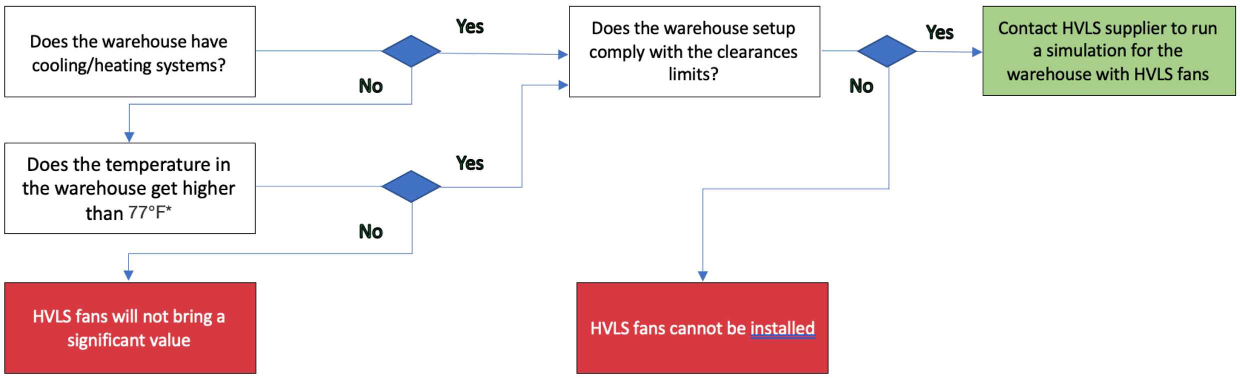
From the results above, it's evident that the HVLS solution works best with a big warehouse layout and the savings can only be captured when they're installed in a large open space in a layout similar to a fulfillment center rather than a small transload warehouse.

4.5.5. Way forward

Based on our research, we advise the organization providing sponsorship to use the following decision-making process when evaluating the feasibility of HVLS fans for future projects.

Figure 23

Roadmap for Scaling Solution to Other Facilities



**Exposure to temperature higher than 77°F (25°C) is considered as a cause for high risk of heat-related illness with strenuous work (Occupational Safety and Health Administration, 2016).*

4.6. Rainwater Harvesting

Over the past 8 years, the world economic forum has been constantly referring to water availability as one of the top five challenges that the world needs to prepare for during the coming years (Akter, 2022). It's estimated that 50% of the world population will be living in areas suffering from water-stress by 2030 (United Nations, 2005). Rainwater harvesting solutions allow for water independence, among many other benefits, are traced back to the Neolithic period or the new stone age (Akter, 2022). The impact of water use on GHG emissions is attributed to the required water extraction, treatment, transportation and disposal activities requiring a significant amount of energy along this supply chain (Griffiths, 2009). As the energy requirement to deliver and dispose one gallon of water in the US is highly dependent on the water sources and terrains, there are no solid recourses that quantified the GHG emissions for water supply in a specific location across the country (International Energy Agency, 2016). Nevertheless, proper water usage is considered as one of key elements of sustainable building as per LEED standard.

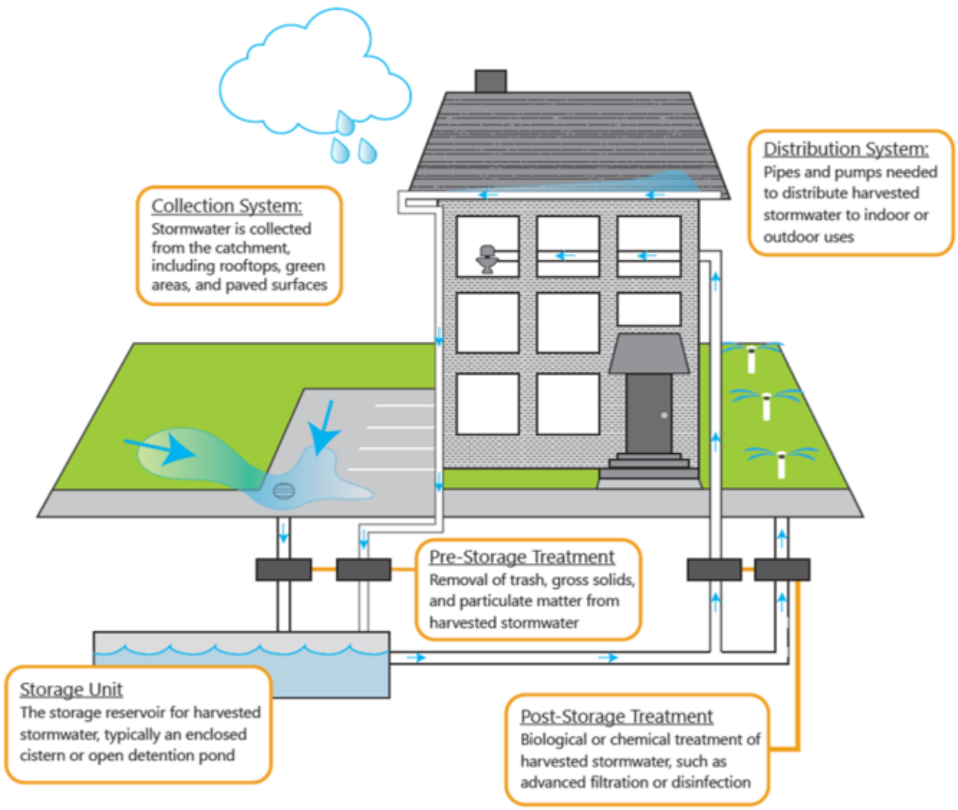
4.6.1. Solution Overview

Rainwater harvesting mainly uses the building's roof area to direct the rainwater into a dedicated reserve to be used instead of the water coming from the municipal water source. If this water will be used in areas with human contact such as toilets, it will need to be processed through a filter which needs to be installed on site. In the US, the filtration system needs to be approved by corresponding authorities in order to ensure the quality of water and the absence of any health risks while being used. In the United States, the authorities responsible for approving a filtration system for rainwater harvesting can vary depending on the state, county, or city where facilities are located. In New Jersey, the Department of Environmental Protection (NJDEP) is responsible for regulating rainwater harvesting systems. The NJDEP has developed guidelines for the design, installation, and maintenance of rainwater harvesting systems, which include requirements for filtration and treatment (Department of Environmental Protection, 2021).

The Figure 24 illustrates the typical rainwater harvesting system (Minnesota Stormwater Manual, 2022). Tanks and filtration systems are usually placed underground, but if space is available, they can also be placed above ground.

Figure 24

Typical Rainwater Harvesting System



When evaluating a rainwater harvesting system, it is crucial to recognize and address the potential risks associated with its implementation and use. The following are some of the key risks to consider (Minnesota Stormwater Manual, 2022):

- Initial investment costs: Installing a rainwater harvesting system can require a significant upfront investment, particularly for larger and more complex systems. This may include the costs of purchasing storage tanks, filters, pumps, and other necessary components, as well as the labor costs for professional installation.

- Water quality and contamination risks: Rainwater collected from rooftops or other surfaces may contain contaminants such as dust, dirt, bird droppings, or chemicals. This presents a risk to water quality, especially if the harvested rainwater is used for drinking, cooking, or other activities requiring potable water. Proper filtration, treatment, and regular water quality testing are crucial to ensure the safety and suitability of the collected rainwater for its intended uses.
- Inconsistent water supply: Rainfall can be highly variable, with seasonal fluctuations and unpredictable weather patterns potentially affecting the reliability of a rainwater harvesting system as a consistent water source. In areas with low or irregular rainfall, supplementary water sources or additional storage capacity may be necessary to meet water demand during dry periods.
- Maintenance requirements: Regular maintenance is essential to ensure the efficiency and safety of a rainwater harvesting system. This may include cleaning and inspecting gutters, filters, and storage tanks, as well as monitoring and maintaining pumps and other mechanical components. Neglecting maintenance can result in reduced system performance, increased risk of contamination, or even system failure.
- Legal and regulatory compliance: In some jurisdictions, there may be regulations or permitting requirements related to rainwater harvesting systems. These regulations can affect system design, installation, and use, and non-compliance may result in fines or other penalties.

A rainwater harvesting system offers numerous benefits that contribute to its appeal as a sustainable and environmentally friendly solution. Key advantages include (Maxwell-Gaines, 2018):

- Water conservation: By collecting and reusing rainwater, these systems reduce reliance on municipal water supplies, leading to more efficient use of water resources and conservation of potable water for essential uses.
- Cost savings: Harvested rainwater can help lower water bills by offsetting the need for municipal water, particularly for non-potable uses such as irrigation, toilet flushing, and cleaning. Additionally, in some regions, users may benefit from rebates or tax incentives for implementing rainwater harvesting systems.
- Reduced stormwater runoff: By capturing rainwater, these systems can help mitigate stormwater runoff, which can contribute to erosion, flooding, and pollution in nearby water bodies. This benefit has positive implications for local ecosystems and stormwater management infrastructure.
- Water supply resilience: Rainwater harvesting systems can enhance water supply resilience by providing an alternative or supplementary source of water during times of drought or water restrictions. This can be particularly beneficial in areas prone to water scarcity or with growing water demand.
- Environmental benefits: Utilizing rainwater reduces the energy and resources required for treating and distributing municipal water, thereby lowering the associated environmental impacts. Furthermore, rainwater harvesting systems support sustainable landscaping practices, promoting the growth of vegetation that contributes to improved air quality and urban biodiversity

4.6.2. Assessment Methodology

Since there is no available information about the greenhouse gas emissions associated with each activity in the water supply chain, we will be conducting our analysis using the direct economic value of the savings generated by reducing water bills.

There are few variables that would determine the demand % that can be covered the collected rainwater:

- Amount of rain (precipitation): usually measured in millimeter or inch.
- Collection surface area in squared feet or squared meter.
- A rainfall of 1 millimeter means that 1 liter of water would accumulate on a 1 square meter surface. Similarly, A rainfall of 1 inch means that ~0.623 gallon of water would accumulate on a 1 square foot surface.
- Tank size: is an important parameter that would allow the system to store water from the rainy days and increase the longevity of supply. It’s important to mention that the tank size has a significant contribution to the project cost.

We start our analysis by estimating the daily historical collectable rainwater (Gallons/Day) from our collection area since 2008 using the following equation:

$$CR = CA * Precipitation * \ Runoff\ coefficient * 0.623$$

Where:

CR: Collectable Rainwater (Gallons) – total collectable regardless of the tank size.

CA: Collection Area (ft^2) – roof area or partial roof area allocated to rainwater harvesting.

Runoff coefficient – “represents loss due to evaporation and leakage the runoff coefficient value ranges from 0.5 to 0.9 for different roofing materials. It’s considered as 0.8 for concrete or steel roofs” (Rawan et al., 2022).

Precipitation (in) – historical location specific data from the website of the National Centers for Environmental Information (www.ncei.noaa.gov).

By having the collectable rainwater and the estimated demand per day we can model how much water a specific tank will have at the end of each day using the following equation:

$$If\ TL(0) + CR(1) - Daily\ Demand > 0, then$$

$$TL(1) = Min\ [TL(0) + CR(1) - Daily\ Demand, Tank\ Size]$$

$$If\ TL(0) + CR(1) - Daily\ Demand < 0, then$$

$$TL(1) = 0$$

Where:

TL(1) (Gallons) – tank level at the end of day 1

TL(0) (Gallons) – tank level at the end of day 0

CR(1) (Gallons) – collectable rainwater during day 1

Daily Demand (Gallons) – water demand estimated from monthly water bills.

Tank size (Gallons) – representing the water storage capacity on site.

Knowing the water level at the end of each day enables us to estimate the building consumption coming from the rainwater harvesting system.

$$If\ TL(1) > 0, then$$

$$\text{CFRS} = Min[Tank\ Size, Daily\ Demand]$$

$$If\ TL(1) = 0, then$$

$$\text{CFRS}\ = TL(0)$$

Where:

CFRS (Gallons) – Consumption from Rainwater System

TL(1) (Gallons) – tank level at the end of day 1

TL(0) (Gallons) – tank level at the end of day 0

Daily Demand (Gallons) – water demand estimated from monthly water bills.

Once we obtain the potential water consumption from the collected rainwater using historical data, we can take the average of collection per month and compare it against the estimated total demand coming from previous water bills.

4.6.3. Assessment for Selected Warehouses

After engaging with a rainwater harvesting solution provider, we realized that retrofitting existing warehouses with rainwater harvesting systems can be costly due to the need of excavation work to fit-in the system underground and the plumbing work to replan the water infrastructure to have it integrated to the water collection system. On the other hand, we believe that incorporating a water harvesting system in the construction plan of new warehouses could significantly lower the costs and make this solution more viable.

Furthermore, the assigned warehouses water consumption levels are very small compared to other industrial building, and this solution can be more economically attractive for those facilities that consume a lot of water. Nevertheless, we ran the model on the assigned warehouses. As showing the Figures 25 and 26 below, a system with a tank size of 1,000 gallons can cover 80% of Facility B's water demand while Facility A can have 80% of the water demand covered by 4,000 gallons tank.

Figure 25

Coverage of Annual Water Demand in Facility B Depending On Tank Size

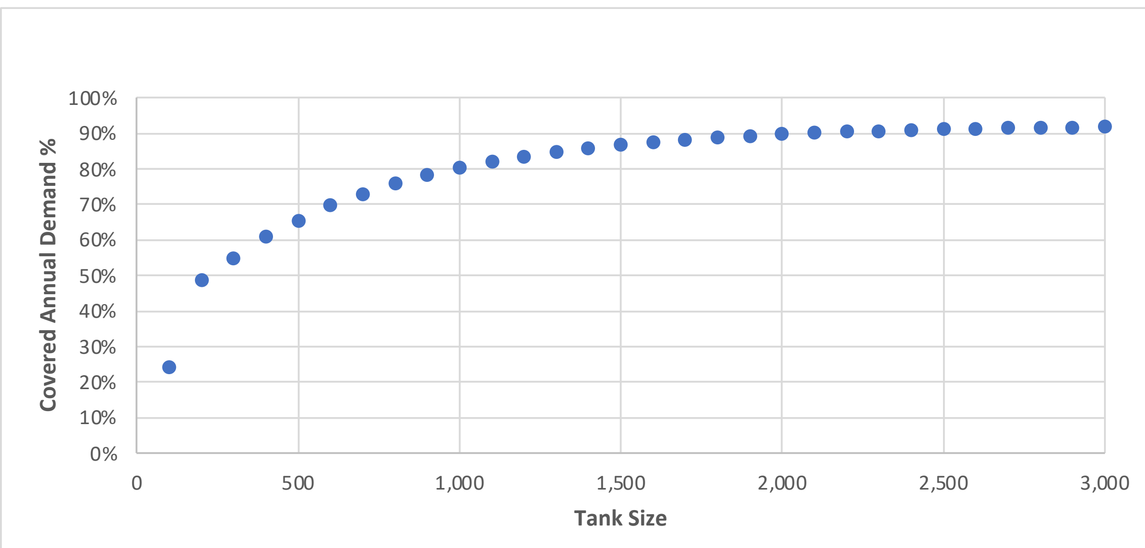
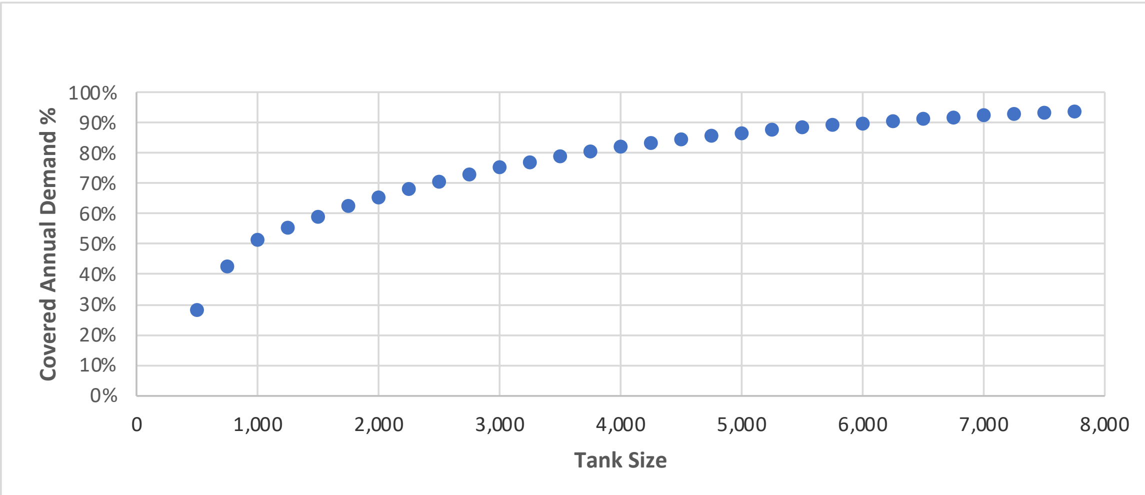


Figure 26

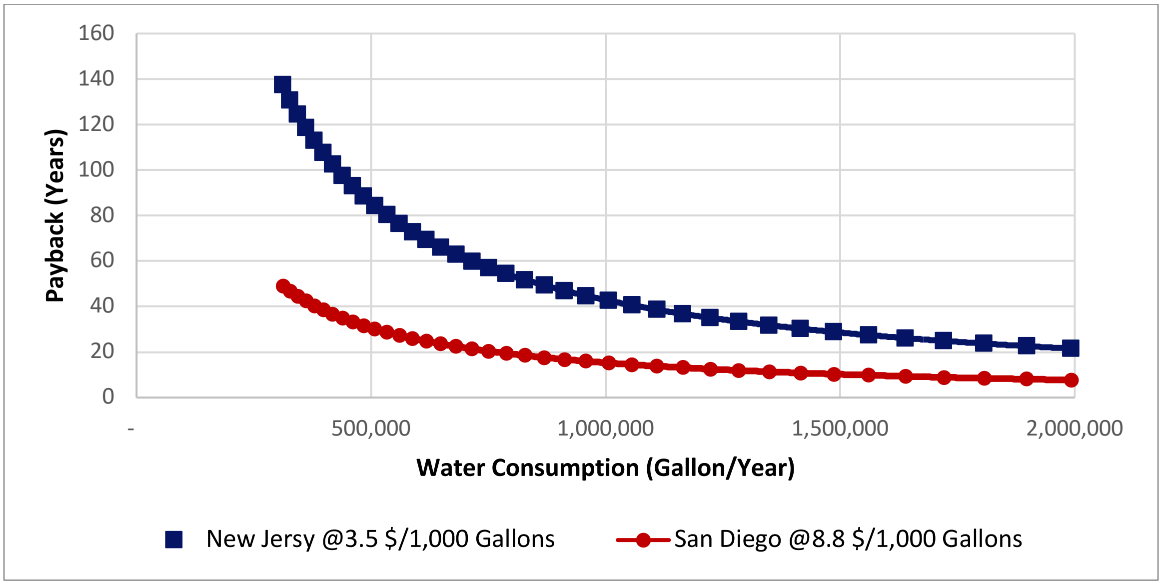
Coverage of Annual Water Demand in Facility A Depending On Tank Size



The cost of a rainwater harvesting system to cover 80% of the demand of those facilities may range between 130,000 to 180,000 USD, and with the minimal amount of the water bills, the payback for this investment will take a very long time that can stretch to couple of decades. Therefore, we do not recommend Maersk to invest in this solution for those facilities or any other existing warehouses with a similar activity. The payback period is a variable to 2 drivers, the water consumption and the cost per gallon. In the figure below, we run the analysis showing 2 locations in the US with different cost per gallon to show the sensitivity of the price along with the water consumption compared to the pay back period. The selected locations are New Jersey and San Diego with water prices coming from several official web-sources (City of Millville, 2022), (City of San Diego Official Website, 2022).

Figure 27

Payback Period per Yearly Water Consumption

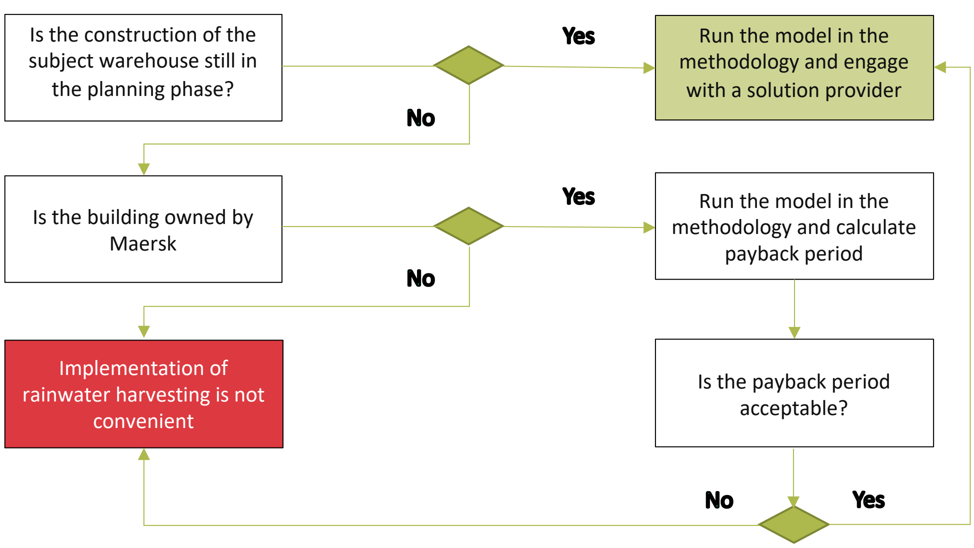


4.6.4. Way Forward

After researching this solution, we recommend the sponsoring organization to follow decision tree when assessing rainwater harvesting in the future as per Figure 28.

Figure 28

Roadmap for Scaling a Solution to Other Facilities



4.7. Overall Results and Discussion

In this section, we provide a general overview of the results of our study, which aimed to assess various solutions for reducing the environmental impact of buildings while considering the payback perspective. In the previous chapter, we established a comprehensive assessment methodology for evaluating potential solutions. Using this methodology, we reviewed and assessed a set of shortlisted solutions, with a specific focus on evaluating their environmental impact and payback potential. By following this well-defined methodology, we can carefully evaluate each solution and make informed decisions about their prioritization based on key performance indicators (KPIs).

However, before ranking the solutions according to our selected key performance indicators (KPIs), it is important to note that all the solutions must be divided into two groups: those that can be implemented without the approval of the building owner and those that require the approval of the building owner.

This distinction is crucial because the sponsoring organization does not own the buildings in which they operate. Therefore, the implementation of some solutions may be limited or not possible without the permission of the building owner. Additionally, investing a large amount of funds to improve a building that the organization does not own may not be advisable.

4.7.1. Solutions Without Facility Modification

As part of our study, we identified four solutions that do not require significant facility modification: electric forklifts, electrified yard tractors, 5 kWh wind turbines and micro wind turbines. Electrified vehicles together with charging stations can be easily integrated into the existing fleet of vehicles and equipment, making them an attractive option for companies that are looking for ways to reduce their carbon footprint without investing in major infrastructure changes. Smaller wind turbines also do not require significant modifications of facility which makes it easier to execute their installation and removal if needed.

Electric forklifts and electrified yard tractors offer several advantages over traditional diesel-powered vehicles, including lower operating costs, reduced emissions, and quieter operation. While the initial cost of purchasing electric vehicles may be higher than traditional vehicles, the long-term cost savings in fuel and maintenance expenses can make up for this difference over time, which was proven in our research.

Furthermore, the reduced environmental impact of electric vehicles can also have a positive impact on a company's reputation, as consumers become increasingly aware of the importance of sustainability and environmental responsibility. Ultimately, shifting to electric vehicles helps to achieve the organization’s environmental goals in terms of Scope 1 and Scope 2 emissions.

Results of KPIs assessment as per developed methodology are presented in Tables 23 and 24 and show that electric forklifts have been found to be the most feasible solution in terms of payback and environmental impact. However, it is important to note that this does not mean that a company should avoid implementing other solutions altogether. Rather, a company should prioritize the implementation of electric forklifts over other technologies when identifying their priorities. The higher environmental impact and better payback numbers in Facility B are due to the higher asset utilization in that location, which results in a greater impact of changing the energy source.

Table 23

Ranking of Solutions Based on KPIs for Facility A (Without Facility Modification)

Solution	Expected payback, years	Annual CO2 reduction, tons	Rank based on payback	Rank based on environmental impact
Electric Forklift	2.47	154.18	1	1
Wind Turbine (5 – kWh)	3.82	21.38	2	3
Electric Yard Goat	6.60	26.00	3	2
Wind Turbine (micro)	8.55	9.57	4	4

Table 24

Ranking of Solutions Based on KPIs for Facility B (Without Facility Modification)

Solution	Expected payback, years	Annual CO2 reduction, tons	Rank based on payback	Rank based on environmental impact
Electric Forklift	1.92	352.41	1	1
Electric Yard Goat	5.00	249.18	2	2
Wind Turbine (micro)	10.33	7.92	3	3

4.7.2. Solutions That Require Facility Modification

However, we also identified several solutions that require facility modification and may require the approval of the building owner. These solutions include high-volume, low-speed (HVLS) fans, solar panels, and 15 kWh wind turbines.

HVLS fans are an energy-efficient alternative to traditional ceiling fans and air conditioning systems. By circulating air more effectively throughout a building, they can reduce the need for air conditioning and improve overall indoor air quality. HVLS fans are also relatively easy to install and can provide significant cost savings in energy expenses over time.

Solar panels and wind turbines are renewable energy solutions that can generate clean energy on-site. While these solutions may require a significant upfront investment, they can provide significant long-term cost savings in energy expenses and reduce the environmental impact of the building. Solar panels can be installed on the roof of a building, while wind turbines can be installed on the surrounding property. However, the installation of solar panels or wind turbines may require the approval of the building owner and may not be feasible for companies that do not own the building.

In addition, there may be limitations on the amount of renewable energy that can be generated on-site due to the size and location of the building or property. The organization may need to supplement on-site renewable energy generation with off-site renewable energy purchases or other solutions to meet their sustainability goals.

Overall, solutions that require facility modification can provide significant environmental and cost benefits in the long run. Company should also engage in discussions with the building owner to determine if these solutions are feasible and obtain the necessary approvals before proceeding with installation.

Table 25

Ranking of Solutions Based on KPIs for Facility A (Requiring Facility Modification)

Solution	Expected payback, years	Annual CO2 reduction, tons	Rank based on payback	Rank based on environmental impact
Solar: PPA	0	333.61	1	1
HVLS fans*	3.95	107.11	2	2
Wind turbines (15 - kWh)	11.15	7.64	3	3

*Analysis for a warehouse with similar configuration in Savannah, GA (300,000 Ft^2)

Table 26

Ranking of Solutions Based on KPIs for Facility B (Requiring Facility Modification)

Solution	Expected payback, years	Annual CO2 reduction, tons	Rank based on payback	Rank based on environmental impact
Solar: PPA	0	48.73	1	1
HVLS fans*	12.48	22.62	2	2
Wind turbines (15 - kWh)	12.67	6.72	3	3

*Done for a warehouse with similar configuration in Chicago, IL (33,000 Ft^2)

As per results of assessment in Table 25, we find that installing solar panels through a PPA agreement is the top ranked solution in both warehouses followed by the HVLS and the 15 kWh wind turbine. Nevertheless, the analysis of all of those solutions is highly dependent on the natural factors in the warehouse location which can highly impact the ranking. Good example is HVLS fans that can bring a significant value when located in areas with higher temperatures to support the air conditioning system in the summer.

Furthermore, as part of our study, we also reviewed the feasibility of rainwater harvesting as a potential solution for reducing the environmental impact of buildings with results presented in Table 26. However, the results of our analysis showed that rainwater harvesting was not feasible for the locations we considered.

While rainwater harvesting can provide a reliable source of non-potable water for non-drinking purposes such as irrigation or toilet flushing, it requires significant investment in infrastructure and maintenance. In addition, it may not be a viable solution in areas with low annual rainfall or limited space for storage tanks.

Our calculations showed that rainwater harvesting may only be considered feasible in cases where the annual cost of water supply exceeds 25,000 USD as a minimum. This cost threshold is important to consider when evaluating the potential payback of rainwater harvesting as a solution.

Coming back to the overview of solutions that lead to decarbonization, it is important to consider the potential economical synergy if solutions are implemented altogether. Thus, implementation of solar and wind would contribute to a faster payback for other solutions due to the cheaper cost of provided electricity leading to payback levels reduced to 4.7 years for yard goats in Facility B and 6.2 years in Facility A. The same impact can be seen for electric forklifts with payback being reduced to 1.7 years in Facility B and 2.25 years in Facility A. All of that represents ~9% improvement of payback for mentioned solutions in case of implementation of solar energy solutions at the level of warehouse.

4.7.3. Final Recommendations

The importance of alternative sources of energy is increasing not only because of electricity cost, but also due to additional benefits that the owner of facility is getting:

- Improved energy independence: Solar energy can help businesses to reduce their reliance on the traditional power grid, providing a degree of energy independence and stability in the face of power outages or disruptions.
- Increased property value: Adding solar panels to a warehouse will increase the property's value, as it is considered a long-term investment in energy efficiency and sustainability.

- Reduced peak demand charges: Solar energy can help businesses to reduce peak demand charges, which are the fees charged by utility companies for using electricity during periods of high demand. By generating their own energy with solar, businesses can avoid these peak charges and save money on their electricity bills.
- Brand differentiation: Adopting sustainable practices, such as using solar energy, can help businesses to differentiate themselves from competitors and demonstrate their commitment to environmental responsibility. This can be a valuable marketing tool and help to attract customers who are environmentally conscious.

Mentioned above factors lead to the following recommendations to Maersk as the next steps following this project:

- Hydrogen: Even though we do not recommend moving to this source of energy due to several constraints mentioned in section 4.1.6., we still suggest the organization to keep track on advance of this technology with the purpose of identification of potential solutions that could eliminate current challenges.
- Ownership of buildings approach: regarding ownership of buildings, we strongly recommend evaluating whether Maersk should own warehouses, based on the following factors:
    - Ownership structure and decision-making: as mentioned before, one of the key factors that can impact the implementation of sustainable solutions in warehouses is the ownership structure of the building. For example, warehouses that are leased to tenants may face challenges in

implementing sustainable solutions if the tenants are responsible for the operational costs and are not incentivized to invest in sustainability. On the other hand, warehouses that are owner-occupied may have more control over the decision-making process and be more motivated to invest in sustainable solutions.

- Tenant requirements and engagement: both landlord’s requirements and engagement can also impact the implementation of sustainable solutions in warehouses. If tenants are not engaged in the sustainability initiatives or do not value them, then the implementation may not be as successful. Therefore, it is important to communicate with tenants and involve them in the decision-making process to ensure that their needs and requirements are considered.
- Increased efficiency: Owning a warehouse can lead to increased efficiency in operations, as there may be fewer restrictions on the use of the facility and its layout. This can result in a more streamlined and efficient workflow, which can ultimately save time and money.
- Real estate appreciation: Real estate values in certain areas may appreciate over time, providing a potential source of investment returns. Owning a warehouse can provide exposure to this potential upside.
- Availability of suitable rental properties: The availability of suitable rental properties may be limited in certain areas, which can make it more attractive to own a warehouse instead. Thus, it is expected that current

warehouse shortages in the US will remain at least till the end of 2025 (Rose Morrison, 2022).

  - Business expansion opportunities: Owning a warehouse can provide opportunities for business expansion or diversification by providing a dedicated and customizable space for new operations or products.

- As Maersk is currently limited by the decisions of warehouse owners regarding investments in solutions that require facility upgrades, we recommend focusing on moving assets (forklifts, yard goats) as the first priority while negotiating with warehouse owners for the implementation of other solutions in parallel.

5. FRAMEWORK

In order to provide a structured approach for evaluating the sustainable solutions identified in this project, we have created a framework that highlights the key factors that could prevent a company from implementing any of the suggested solutions and other factors that define the profitability of adopting such solutions in any building.

This framework offers a systematic and holistic approach to the problem-solving by helping companies to identify key factors, relationships, and patterns that can influence the outcomes of investing in any of the solutions studied in this project. It also helps establishing a common language and understanding between the stakeholders involved in the problem-solving process to help facilitating communication, collaboration, and alignment.

5.1. Classification of Sustainable Solutions

The solutions highlighted in the framework can be classified into three main categories depending on the extent of modifications required to be done to the building structure during their implementation and removal.

The first category, moving assets, includes solutions that can be easily relocated from one facility to another with all the applicable infrastructure. These solutions are distinguished by their significant portability and minimal need for modifying the facility.

The second category, semi-fixed assets, includes solutions that require a relatively low level of facility modifications to install and remove them. These solutions are typically designed for a specific purpose and can be easily integrated into existing facilities without significant structural changes.

The third category, fixed assets, includes solutions that require significant modifications to the facility for their installation and removal. These solutions are typically more permanent in nature and require major structural changes to the facility.

By categorizing the solutions in this way, we can better understand their characteristics and requirements, and make informed decisions about their feasibility and suitability for the specific needs of each project.

5.2. Key Factors Affecting Feasibility and Payback Period

The developed framework offers a comprehensive set of the key factors that need to be considered when evaluating sustainable solutions in an integrated way. These aspects are divided into two categories based on their nature: factors that affect the feasibility of the project and factors that affect the payback period.

- Feasibility factors define the ease of implementing each solution at the warehouse and can highlight important elements that need to be considered before approaching each solution, such as:
    - Ownership of the Facility: indicates the importance of owning the facility as a requirement for adopting the solution. This can be a result of requiring significant modification to the building structure or having a payback period beyond the usual building lease duration.
    - HVAC Presence: specifies weather the applicability of the solution is dependent on whether the warehouse has a controlled temperature or not.
    - Regulations and Permits: assesses the complexity of regulations and permits required for implementing a solution.

    - Implementation Time: varies among solutions, depending on their complexity and the extent of facility and surrounding area modifications needed.
- Payback period factors are the ones affecting the payback duration and overall economic attractiveness of a solution, and stakeholders need to pay special attention to them as they highly differ from one warehouse to another, which may yield very different economic feasibility; such as:
    - Government Incentives: highlights the importance of the presence of state incentives on the economic viability of the solution.
    - Fuel Cost: measures how fuel supply costs, such as diesel or propane, influence a solution's economic feasibility.
    - Electricity Cost: assesses the impact of electricity costs on the payback of a specific solution and its economic attractiveness.
    - Initial Investment: evaluates the amount of initial investment needed to implement the solution.
    - Asset Utilization: measures how the utilization level of an asset impacts the economic attractiveness and payback period for a specific solution.
    - Atmospheric Factors: gages the extent to which a company should take into account specific atmospheric factors, such as precipitation levels or irradiance strength, before analyzing a solution. This is because those factors can heavily influence the performance and economic feasibility of a solution.

Factors that affect the environmental impact of the solutions were not included in the framework due to being very specific for each solution. For example, a warehouse located in areas subject to high wind speed would naturally find that installing wind turbines can get them closer to their intended sustainability targets.

5.3. Framework Development

To build the framework, we thoroughly examined each of the categories of sustainable solutions, taking into account the factors mentioned earlier. We assigned each factor a criticality ranking based on its impact on feasibility and payback period, utilizing a three-tiered system: high, medium, and low criticality. The framework is presented in Table 27.

Table 27

Framework for an Integrated Evaluation of Sustainable Solutions in a Warehouse

		Moving Assets		Semi Fixed Assets		Fixed Assets		
	Key Factors	Forklifts	Yard Goats	HVLS Fans	Wind (mobile)	Solar Energy	Wind (fixed)	Rainwater Harvesting
Feasibility	Ownership of the Facility	Green	Green	Yellow	Yellow	Red	Red	Red
	HVAC Presence	Grey	Grey	Red	Green	Yellow	Green	Grey
	Regulations and Permits	Green	Green	Green	Green	Yellow	Red	Red
	Implementation Time	Yellow	Yellow	Green	Yellow	Red	Red	Red
Payback Period	Government Incentives	Green	Green	Green	Green	Red	Red	Red
	Fuel Cost	Red	Red	Yellow	Grey	Grey	Grey	Grey
	Electricity Cost	Red	Red	Yellow	Green	Yellow	Green	Grey
	Initial Investment	Yellow	Red	Green	Green	Green	Yellow	Red
	Asset Utilization	Red	Red	Grey	Yellow	Yellow	Yellow	Grey
	Atmospheric Factors	Grey	Grey	Yellow	Red	Red	Red	Red

Legend:

Criticality of each factor	
High	(red circle)
Medium	(yellow circle)
Low	(green circle)
Not Applicable	(grey circle)

Establishing different levels of criticality for each solution is key to gain a comprehensive understanding of what the feasibility and the payback period of any sustainable solution is subject to. For example, when considering electrifying the forklifts fleet in a warehouse, the reader can infer that this solution is relatively easy to implement as it does not require significant building modifications, and typically does not need an approval from the building owner. Electric forklifts are not subject to strict regulations or standards, which signifies the low importance of these factors as per the framework for the solution's implementation.

Incentives also have a low importance in impacting the economic attractiveness of the solution. Instead, the savings a company can achieve due to the cost difference in energy consumption (electricity is typically cheaper than propane or diesel) play a significant role. Therefore, the importance of cost of fuel and energy is high for the economic feasibility of electric forklifts as a solution. Required upfront costs primarily depend on the forklift fleet size but are generally smaller compared to other, more complex solutions like solar panels.

While the implementation of electric forklifts can be faster than rainwater harvesting, it might still take longer than installing HVLS fans. This is primarily due to the extended manufacturing lead time of electric forklifts from suppliers. Nonetheless, understanding these factors helps parties make informed decisions about the most suitable and feasible solutions for their warehousing operations.

5.4. Integrated Analysis of Sustainable Solutions Categories

Finally, the framework also helps identify common patterns for each category.

The impact of installing sustainable moving assets, such as forklifts and yard goats, is highly dependent on their utilization to determine their economic attractiveness, which is a function of the cost of electricity and fuel as mentioned above. A greater difference between these costs drives payback towards a faster timeline considering the high value of the required up-front costs. Additionally, this category is characterized by low dependence on the building owner's potential restrictions, as their implementation does not require a modification to the facility. Typically, this group of solutions is characterized by a relatively shorter payback period.

Furthermore, the implementation of moving assets typically does not require the facility owner to obtain any specific permits, and can be implemented relatively quickly, as they only require the installation of charging infrastructure.

Semi-fixed assets such as HVLS fans and mobile wind turbines are more dependent on electricity costs for economic attractiveness. Investing in semi-fixed assets can help to reduce the electricity consumption for a specific purpose or eliminate a certain point of electricity supply from the grid. Both HVLS fans and mobile wind turbines are characterized by low upfront costs. Similar to moving assets, semi-fixed assets are typically not subject to any specific regulations and can be implemented relatively quickly. On the other hand, unlike moving assets, the feasibility of implementing this category of solutions can be subject to natural factors such as the average temperature or wind speed at the location of the warehouse. Both solutions require moderate modifications to a building's structure, a moderate level of electricity supply network modification, and easy installation work on the ceiling and rooftop.

Fixed assets such as solar panels, rainwater harvesting systems, and fixed wind turbines require significant modifications of a building and its structure, which require proper approval and readiness of the building owner to implement such solutions. Rainwater harvesting together with fixed wind turbines are both characterized by a longer payback period. The timeline of their implementation is also much longer compared to the rest of the solutions. All solutions require high upfront investment, and even though solar does not require any for the company due to the considered commercial model (PPA), it is still required for a service provider. Therefore, the importance of incentives is increasing compared to other reviewed solutions as they help offset some of the upfront costs to bring the solution to the level of profitability.

Finally, the feasibility for on-site solar and wind energy generation is highly dependent on the natural factors and the utilities costs. Natural factors contribute to the outcome of energy or water produced by the relevant system, while the cost of utilities defines the current level of costs the company is trying to offset.

6. CONCLUSION

Sustainability has become a critical topic for companies in the 21st century due to increasing pressures from stakeholders, regulations, and customers. The global transportation industry is not an exception, and companies are seeking ways to reduce their environmental impact and improve their social responsibility while maintaining their competitiveness.

Maersk, a worldwide transportation and supply chain solutions leader, has taken significant steps towards reducing its carbon footprint. The organization has set a decarbonization goal of achieving net-zero emissions for all its businesses by 2040. In the pursuit of their sustainability vision, Maersk has also established a roadmap for decarbonizing their warehouses. This initiative is a positive step towards a greener future for the organization and the world at large.

To achieve their warehousing decarbonization goals, Maersk undertook a research project that focused on two specific facilities as an object of research: one fulfillment and one transload warehouse. The project analyzed various resources to gain an understanding of what constitutes a sustainable warehouse from a scientific perspective and how the industry views this question. We thoroughly studied the Greenhouse Gas Protocol to learn the most common approach for assessing the environmental impact and quantifying greenhouse gas emissions at each warehouse.

Drawing on the analyzed sources of information, the research project developed a methodology that helped to identify key sources of emissions at each warehouse. This enabled us to pinpoint potential solutions to offset such emissions and reduce the carbon footprint of Maersk's warehouses. Despite the fact of not having a measurable GHG emission impact, we decided to explore the rainwater harvesting as a solution that can enhance the sustainability of a warehouse further.

To ensure that the identified potential solutions were technically feasible, economically viable, and aligned with industry practices, we reviewed each solution from various perspectives including examining current trends, industry practices, limitations, and key cost drivers. After a thorough review, a separate methodology was developed for each potential solution that can serve as a roadmap to assess the solution's environmental impact and evaluate its required investment payback period.

Based on the assessment of potential solutions, the research project developed a set of recommendations for Maersk. These recommendations included a prioritization of solutions based on their environmental impact and payback period. In addition, the team provided insights on aspects such as warehouse ownership, which can have a significant impact on the feasibility of some of identified solutions.

By considering these recommendations, Maersk can make informed decisions that support their sustainability goals while also optimizing their warehouse operations.

The ultimate outcome of this research project is the development of a framework which provides a structured approach that can be used when assessing sustainable solutions. This applicable framework offers a systematic and holistic approach to identifying potential sustainable solutions, enabling companies to identify key factors, relationships, and patterns that can influence outcomes. By establishing a common language and understanding for the stakeholders involved in the problem-solving process, this framework facilitates communication, collaboration, and alignment. It represents a valuable contribution to the broader effort to build a more sustainable future, providing a tool that can be used by any company seeking to reduce their carbon footprint.

6.1. Future Research

This study has laid the groundwork for evaluating various sustainable solutions in warehouse management. However, future research should focus on emerging technologies and innovative approaches, such as hydrogen fuel cells and fast-charging systems, to further enhance the sustainability and efficiency of warehouse operations. Specifically, researchers should concentrate on the development and advancement of hydrogen-based solutions, addressing the current challenges associated with the cost of infrastructure and storage. By exploring novel methods to overcome these obstacles, the potential of hydrogen as a clean and efficient energy source can be fully realized, making it a viable option for sustainable warehouse operations. In addition, fast-charging technology should be investigated to minimize downtime and improve the productivity of electric-powered equipment, such as forklifts and yard goats. By directing research efforts towards these areas, the warehouse industry can continue to progress towards a more environmentally responsible and economically viable future.

The framework proposed already identified key factors based on the six sustainable solutions analyzed in this capstone. Further research can be conducted in this topic, revisiting and including more key factors when analyzing different solutions. Finally, the framework can be expanded including the scalability of each additional solution.

References

ABB. (2022). *How to retrofit your Food & Beverage plant to enhance power monitoring and increase energy efficiency*. https://explore.abb.com/beyondconnected-applicationnote-foodandbev/index.html

Action Lift. (2020). *HVLS Fans–Beat the Heat with a Breeze!* https://www.actionliftinc.com/about/blog/hvls-fans-beat-the-heat-with-a-breeze.html#:~:text=The%20advantage%20of%20HVLS%20fans,by%2010%2D12%20degrees%20F.

AdapdaliftGroup. (2021). *How Much Electricity does a Forklift Use per Hour?* https://www.adaptalift.com.au/blog/how-much-electricity-does-a-forklift-use-per-hour

Agility. (2021). *Green Warehousing & Sustainable Warehouse*. Agility. https://www.agility.com/en/blog/what-is-green-warehousing-how-sustainable-warehouses-can-satisfy-stakeholders-improve-the-bottom-line-and-prioritize-the-planet/

Akter, A. (2022). *Rainwater Harvesting—Building a Water Smart City*. Springer International Publishing. https://doi.org/10.1007/978-3-030-94643-2

Alternative Fuels Data Center. (2020). *Cost of Hydrogen Fuel*. https://afdc.energy.gov/fuels/hydrogen_fuel_cost.html

Amazon. (2021). *Amazon's 2021 Sustainability Report* (Sustainability Report 2021). https://sustainability.aboutamazon.com/2021-sustainability-report.pdf

Amed, I., Berg, A., Balchandani, A., Hedrich, S., Rolkens, F., Young, R., & Ekelof, J. (2020). The State of Fashion 2020. *Business of Fashion and McKinsey & Company: New York, NY, USA*.

American Automobile Association. (2023). *Gas Prices: National and State Average*. https://gasprices.aaa.com/?state=NJ

A.P. Moller - Maersk. (2021a). *A. P. Moller—Maersk to acquire LF Logistics, a premium omnichannel fulfilment company | Maersk*. https://www.maersk.com/news/articles/2021/12/21/apmm-to-acquire-lf-logistics/

A.P. Moller - Maersk. (2021b). *Maersk Sustainability Report 2021* (Sustainability Report 2021). https://www.maersk.com/~/media_sc9/maersk/corporate/sustainability/files/resources/2021/maersk-sustainability-report_2021.pdf

A.P. Moller - Maersk. (2022). *Warehouse management – an integral part of a strong supply chain*. https://www.maersk.com/insights/integrated-logistics/warehouse-management-for-strong-supply-chain

Bristowe, G., & Smallbone, A. (2021). The Key Techno-Economic and Manufacturing Drivers for Reducing the Cost of Power-to-Gas and a Hydrogen-Enabled Energy System. *Hydrogen*, *2*(3), 273–300. https://doi.org/10.3390/hydrogen2030015

Canadian Wind Energy Association. (2013). *Small Wind Turbine Purchasing Guide: Off-grid, Residential, Farm & Small Business Applications*. https://web.archive.org/web/20130302211547/http:/www.ontario-sea.org/Storage/39/3065_Small_Wind_Turbine_Purchasing_Guide_-_Off-grid%2C_Residential%2C_Farm_%26_Small_Business_Applications.pdf

Casini, M. (2015). Smart windows for energy efficiency of buildings. *International Journal of Civil and Structural Engineering – IJCSE Volume 2 : Issue 1 [ISSN : 2372-3971]*, *2*, 2372–3971.

CBS. (2022). *Shortage Of Hydrogen Stations Leads To Fill-Up Frustrations For Drivers*. https://www.cbsnews.com/sacramento/news/hydrogen-station-fill-up-frustrations/

Chang J. H., & Ng J. C. (2021). From Air-conditioned Modernity to Lower-Carbon Alternatives: The case of Singapore responding to the Climate Crisis. *Elements*. https://scholarbank.nus.edu.sg/handle/10635/194252

Chen, C., & Energy, P. S. (2007). Case Studies: Infrared Heating in Industrial Applications. *ACEEE Summer Study on Energy Efficiency in Industry*.

Cisco-Eagle. (2020). *Justifying HVLS Big Ass Fans*. https://www.cisco-eagle.com/category/3157/justifying-a-high-volume-low-speed-fan

City of Millville. (2022). *Water Rates*. http://www.millvillenj.gov/211/Water-Rates

City of San Diego Official Website. (2022). *Water Billing Rates*. https://www.sandiego.gov/public-utilities/customer-service/water-and-sewer-rates/water#:~:text=The%20total%20bill%20for%20Commercial,find%20the%20meter%20base%20fee.

CK Power. (2015). Final Tier 4 Engines: A Visual Guide to Regulations. *CK Power*. https://ckpower.com/visual-guide-to-regulations-for-final-tier-4-engines/

Compare Propane. (2023). *New Jersey Propane Prices for 2023*. https://www.comparepropane.com/new-jersey-propane-prices/

Conger. (2021). *Electric Forklifts vs. Propane: Which Is Better?* Conger Industries Inc. https://www.conger.com/electric-forklifts-vs-propane/

Department of Energy. (2007). *Small Wind Electric Systems: A U.S. Consumer's Guide*. https://www.nrel.gov/docs/fy07osti/42005.pdf

Department of Energy. (2014). *Energy Conservation Program for Consumer Products: Test Procedure for Ceiling Fans* (No. 6450-01-P). Department of Energy. https://www.energy.gov/sites/prod/files/2014/09/f18/ceiling_fans_nopr.pdf

Department of Energy. (2019). *IECC climate zone map*. https://basc.pnnl.gov/images/iecc-climate-zone-map

Department of Energy. (2021). *Wind Vision*. https://www.energy.gov/eere/wind/wind-vision-1

Department of Energy. (2022a). *Small Wind Electric Systems*. https://www.energy.gov/energysaver/small-wind-electric-systems

Department of Energy. (2022b). *Wind Turbines: The Bigger, the Better*. https://www.energy.gov/eere/articles/wind-turbines-bigger-better

Department of Environmental Protection. (2021). *Post-Construction Stormwater Management*.

DHL. (2019). *Next on the green agenda for logistics: Energy-efficient warehouses*. https://lot.dhl.com/next-on-the-green-agenda-for-logistics-energy-efficient-warehouses/

Doherty, S., & Hoyle, S. (2009). *Supply Chain Decarbonization and the Role of Logistics and Transport in Reducing Supply Chain Carbon Emission*. World Economic Forum, Geneva. https://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf

Electrification Coalition. (2022). Inflation Reduction Act Impacts on Electric Vehicles. *Electrification Coalition*. https://electrificationcoalition.org/work/federal-ev-policy/inflation-reduction-act/

Energy Star. (2022). *Cool Roofs*. https://www.energystar.gov/products/roof_products/cool_roofs_emissivity

EnergySage. (2023). *Electricity Cost in Burlington, NJ: 2023 Electric Rates*. https://www.energysage.com/local-data/electricity-cost/nj/burlington-county/burlington/

EPA. (2014). *Emission Factors for Greehouse Gas Inventories*. https://www.epa.gov/sites/default/files/2015-07/documents/emission-factors_2014.pdf

EPA, O. (2021). *Power Profiler*. https://www.epa.gov/egrid/power-profiler

FirstEnergy. (2022). *Electric Forklift Facts: Savings and analysis*. https://www.firstenergycorp.com/content/dam/customer/products/files/Electric-Forklift-Fact-Sheet.pdf

Flux Power. (2022). *Which of These Types of Forklift Is Best? Here's the Answer*. https://www.fluxpower.com/choosing-the-right-forklift-power-source

Gardner, T. (2022). Climate change could cost U.S. budget $2 trillion a year by the end of the century, White House says. *Reuters*. https://www.reuters.com/world/us/exclusive-climate-change-could-cost-us-budget-2-trln-year-by-end-century-white-2022-04-04/

Grand View Research. (2022). *Material Handling Equipment Market Size Report, 2022-2030*. https://www.grandviewresearch.com/industry-analysis/materials-handling-equipment-market

Grant, T. (2022). *Which states have solar incentives?* ADT Solar. https://www.adtsolar.com/blog/state-solar-incentives/

Greenhouse Gas Protocol. (2022). *Companies and Organizations*. https://ghgprotocol.org/companies-and-organizations

Griffiths, B. (2009). *The Carbon Footprint of Water*. River Network. https://www.csu.edu/cerc/researchreports/documents/CarbonFootprintofWater-RiverNetwork-2009.pdf

Huang, X., Hu, Z., Liu, C., Yu, D., & Yu, L. (2016). The relationships between regulatory and customer pressure, green organizational responses, and green innovation performance. *Journal of Cleaner Production*, *112*, 3423–3433.

Hydrogen Fuel Cell Partnership. (2020). *Air Products Statement for Hydrogen Supply Shortage*. https://h2fcp.org/blog/air-products-statement-hydrogen-supply-shortage

Hydrogen Fuel News. (2022). *Hydrogen Forklifts: Future of Technology?* https://www.hydrogenfuelnews.com/cost-of-a-hydrogen-fuel-cell-forklift/

Hy-Tek. (2023). *Lithium Ion vs Lead Acid Forklift Batteries | Which is Better?* https://hy-tek.com/resources/lithium-ion-vs-lead-acid-forklift-batteries-which-is-best-for-you/

IEMA. (2017). *Assessing Greenhouse Gas Emissions and Evaluating their Significance*. IEMA. https://www.iema.net/preview-document/assessing-greenhouse-gas-emissions-and-evaluating-their-significance

Inbound Logistics. (2013). *Creating a Greener Warehouse*. Inbound Logistics. https://www.inboundlogistics.com/articles/creating-a-greener-warehouse/

International Energy Agency. (2016). *WEO-2016 Special Report: Water-Energy Nexus – Analysis*. IEA. https://www.iea.org/reports/water-energy-nexus

International Energy Agency. (2019). *Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050*. IEA. https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050

Katzin, D., Marcelis, L. F. M., & van Mourik, S. (2021). Energy savings in greenhouses by transition from high-pressure sodium to LED lighting. *Applied Energy*, *281*, 116019. https://doi.org/10.1016/j.apenergy.2020.116019

Kriss, J. (2014). *What is green building?* U.S. Green Building Council. https://www.usgbc.org/articles/what-green-building

Kuhn, B. T., Pitel, G. E., & Krein, P. T. (2005). Electrical Properties and Equalization of Lithium-Ion Cells in Automotive Applications. *2005 IEEE Vehicle Power and Propulsion Conference*, 55–59. https://doi.org/10.1109/VPPC.2005.1554532

Levinson, R., & Akbari, H. (2010). Potential benefits of cool roofs on commercial buildings: Conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. *Energy Efficiency*, *3*(1), 53–109. https://doi.org/10.1007/s12053-008-9038-2

Linde Material Handling. (2016). *Electric vs. Hydrogen Powered Forklifts*. KION North America. https://blog.kion-na.com/electric-vs-hydrogen-powered-forklifts/

Lindsey, R., & Dahlman, L. (2021). *Climate Change: Global Temperature | NOAA Climate.gov*. Climate Change: Global Temperature. https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

Malinowska, M., Rzeczycki, A., & Sowa, M. (2018). Roadmap to sustainable warehouse. *SHS Web of Conferences*, *57*, 01028.

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2009). *Wind Energy Explained: Theory, Design and Application* (1st ed.). Wiley. https://doi.org/10.1002/9781119994367

Maxwell-Gaines, C. (2018). The Many Benefits and Advantages of Rainwater Harvesting. *Innovative Water Solutions LLC*. https://www.watercache.com/faqs/rainwater-harvesting-benefits

Metzger, N., & Li, X. (2022). Technical and Economic Analysis of Fuel Cells for Forklift Applications. *ACS Omega*, *7*(22), 18267–18275. https://doi.org/10.1021/acsomega.1c07344

Minnesota Stormwater Manual. (2022). *Environmental concerns for stormwater and rainwater harvest and use/reuse* -. https://stormwater.pca.state.mn.us/index.php/Environmental_concerns_for_stormwater_and_rainwater_harvest_and_use/reuse

Mohamed, N. A. S., Shari, Z., Dahlan, N. D., & Idowu, I. A. (2021). Architectural Sustainability on the Impacts of Different Air-Conditioning Operational Profiles and Temperature Setpoints on Energy Consumption: Comparison between Mosques with and Without HVLS Fan in the City Center Mosques. *Journal of Design and Built Environment*, *21*(2), Article 2. https://doi.org/10.22452/jdbe.vol21no2.3

Morecroft, D. (2022). *Emerging Technologies for the Built Environment—Smart Windows Enhancing the Energy Efficiency of Buildings*. COINS Global. https://www.coins-global.com/services/smart-windows-enhancing-the-energy-efficiency-of-buildings/2381/

National Atmospheric and Oceanic Administration. (2022). *Climate*. https://www.noaa.gov/climate

National Fire Protection Association. (2013). *Application of HVLS Fans*. https://web.p.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=0&sid=d6b97622-88bc-4a1d-9ab3-f82b85e25dd9%40redis

National Renewable Energy Laboratory. (2019). *Operating Hydrogen Forklifts*. https://www.nrel.gov/docs/fy15osti/63166.pdf

North American Council for Freight Efficiency. (2022a). *Electric Trucks Have Arrived: The Use Case for Terminal Tractors*.

North American Council for Freight Efficiency. (2022b). *Terminal Tractors: Market Segment and Fleet Profile*. https://nacfe.org/wp-content/uploads/2022/01/Terminal-Tractors-RoL-E-Fact-Sheet.pdf

Occupational Safety and Health Administration. (2016). *Heat Hazard Recognition*. https://www.osha.gov/heat-exposure/hazards

Occupational Safety and Health Administration. (2019). *Preventing Fire and/or Explosion Injury from Small and Wearable Lithium Battery Powered Devices*. https://www.osha.gov/sites/default/files/publications/shib011819.pdf

Occupational Safety and Health Administration. (2023). *Storage and handling of liquefied petroleum gases*. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.110

Parts Brite. (2018). *Tips for Making Your Loading Dock More Energy-Efficient In the Summer*. Parts Brite. https://partsbrite.com/blogs/news/tips-for-making-your-loading-dock-more-energy-efficient-in-the-summer

Patterson, M., Singh, P., & Cho, H. (2022). The current state of the industrial energy assessment and its impacts on the manufacturing industry. *Energy Reports*, *8*, 7297–7311. https://doi.org/10.1016/j.egyr.2022.05.242

Petrochemical, Chemical & Engineering. (2022). *How Much Does a Gallon of Hydrogen Fuel Cost?* https://www.petro-online.com/news/measurement-and-testing/14/breaking-news/how-much-does-a-gallon-of-hydrogen-fuel-cost/57718

Ranpak. (2022). 3 Trends Elevating The Importance of Green Warehousing. *Ranpak*. https://www.ranpak.com/blog/2022/01/26/green-warehouse/

Rawan, B., Ullah, W., Ullah, R., Akbar, T. A., Ayaz, Z., Javed, M. F., Din, I., Ullah, S., Aziz, M., Mohamed, A., Khan, N. A., & Khan, O. (2022). Assessments of Roof-Harvested Rainwater in Disctrict Dir Lower, Khyber Pakhtunkhwa Pakistan. *Water*, *14*(20), 3270. https://doi.org/10.3390/w14203270

Refresh Fans. (2021). *5 Most Common Mistakes While Installing HVLS Fans*. https://refreshfans.com/5-most-common-mistakes-while-installing-hvls-fans/

Ries, J., Grosse, E., & Fichtinger, J. (2016). Environmental impact of warehousing: A scenario analysis for the United States. *International Journal of Production Research*, *55*. https://doi.org/10.1080/00207543.2016.1211342

Roberts Gordon. (2022). *VIRTUAL WALL integrated HVAC system for industrial buildings*. https://www.robertsgordon.com/virtualwallindustrialhvac

Rose Morrison, G. (2022). *Is the Industrial Warehouse Shortage Temporary?* [All Things Supply Chain]. https://www.allthingssupplychain.com/is-the-industrial-warehouse-shortage-temporary/

RT Fans. (2019). *What is the difference between an HVLS fan and a traditional fan?* https://koolairint.com/faqs/what-is-the-difference-between-an-hvls-fan-and-a-traditional-fan.html

Rüdiger, D., Schön, A., & Dobers, K. (2016). Managing Greenhouse Gas Emissions from Warehousing and Transshipment with Environmental Performance Indicators. *Transportation Research Procedia*, *14*, 886–895.

Rutgers Center for Green Building. (2022). *Benefits of Green Buildings*. http://rcgb.rutgers.edu/benefits-of-green-buildings/

S&P Global. (2023). *Experts explain why green hydrogen costs have fallen and will keep falling*. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/experts-explain-why-green-hydrogen-costs-have-fallen-and-will-keep-falling-63037203

Sunol, H. (2021). *How to Achieve a Sustainable Warehouse*. Cyzerg. https://articles.cyzerg.com/sustainable-warehouse-how-to-achieve

Tan, K.-S., Ahmed, M. D., & Sundaram, D. (2009). Sustainable warehouse management. *Proceedings of the International Workshop on Enterprises & Organizational Modeling and Simulation*, 1–15.

The Foundation For Future Supply Chain. (2022). *Case Study: UPS Sustainable Warehouse Technology*. https://futuresupplychains.org/ups-sustainable-warehouse-technology/

The Renewable Energy Hub. (2022). Large Scale & Commercial Rainwater Harvesting. *The Renewable Energy Hub*. https://www.renewableenergyhub.co.uk/main/rainwater-harvesting-information/large-scale-commercial-rainwater-harvesting/

Thunder Said Energy. (2020). *How is the power of a wind turbine calculated?* https://thundersaidenergy.com/downloads/wind-power-impacts-of-larger-turbines/#:~:text=The%20best%20overall%20formula%20for,(in%20meters%20per%20second).

Toyota. (2020). *Forklift Fuel Consumption & Efficiency*. https://www.toyotaforklift.com/resource-library/blog/energy-solutions/forklift-fuel-consumption-efficiency#:~:text=Internal%20combustion%20forklifts%20consume%20approximately,of%20LPG%20per%20hour.

United Nations. (2005). *International Decade for Action "Water for Life" 2005-2015. Focus Areas: Water scarcity*. https://www.un.org/waterforlifedecade/scarcity.shtml

United Nations. (2019). *Sustainability*. United Nations. https://www.un.org/en/academic-impact/sustainability

United Nations. (2020). *Sustainable Development*. https://www.un.org/ecosoc/en/sustainable-development

U.S. Energy Information Administration. (2017). *More than half of utility-scale solar photovoltaic systems track the sun through the day*. https://www.eia.gov/todayinenergy/detail.php?id=30912

U.S. Energy Information Administration. (2018). *Electricity in the U.S.* https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

U.S. Energy Information Administration. (2022). *Annual Electric Generator Report*. https://www.eia.gov/electricity/data/eia860/

U.S. Energy Information Administration. (2023a). *Carbon Dioxide Emissions Coefficients*. https://www.eia.gov/environment/emissions/co2_vol_mass.php

U.S. Energy Information Administration. (2023b). *New Jersey State Energy Profile*. https://www.eia.gov/state/print.php?sid=NJ,

U.S. Green Building Council. (2022a). *LEED rating system*. https://www.usgbc.org/leed

U.S. Green Building Council. (2022b). *Mission and vision*. https://www.usgbc.org/about/mission-vision

Walker, S. (2021). Compare LPG Forklift to Hydrogen Forklift. *Lean Inc*. https://leanmh.com/compare-lpg-forklift-to-hydrogen-forklift/

Watson, M. (2022). *How HVLS Fans in the Workplace Create a Healthier Environment*. Gb&d Magazine. https://gbdmagazine.com/hvls-fans-workplace/

XPO Logistics. (2017). *Commitment to Sustainability*. https://europenews.xpo.com/en/1568/xpo-commits-to-emissions-control-fuel-efficiency-and-green-logistics/

Zeng, H. (2011). *Integration of renewable energy with urban design: Based on the examples of the solar photovoltaics and micro wind turbines* [PhD Thesis]. Massachusetts Institute of Technology.

Zhou, Y., Fan, F., Liu, Y., Zhao, S., Xu, Q., Wang, S., Luo, D., & Long, Y. (2021). Unconventional smart windows: Materials, structures and designs. *Nano Energy*, *90*, 106613. https://doi.org/10.1016/j.nanoen.2021.106613

Zohuri, B. (2019). *Hydrogen Energy: Challenges and Solutions for a Cleaner Future*. Springer International Publishing. https://doi.org/10.1007/978-3-319-93461-7