Determining the Viability of Retrofitting HVAC and Lighting Systems of Warehouses in the United States

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CE286E
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December 06, 2018

Executive Summary

The main objective of this report is to illustrate how go/no-go decisions can be taken regarding the retrofitting of lighting and HVAC systems in warehouses all over the United States. These decisions are important to owners as they could result in cost savings through lower utility bills, and to regulators as they could result in greenhouse gas emission reductions. In the US, according to CBRE[1] research, nearly 1 billion square-feet of total warehouse inventory is more than 50 years old. In addition, the US Bureau of Labor statistics reports (in workplace trends section) states that 98% of all establishments in the "Warehousing and Storage: NAICS 493" sub-sector are privately owned, and their number increased from 15,203 in 2008 to 17,991 by the end of 2017.[2]

This report is inspired by a paper "Multi-Aspect Energy Performance of Building Form in Eight U.S. Climate Zones"[3] in which the authors have compared several energy saving measures and ranked the energy saving potentials of multiple parameters for typical building types in all 8 U.S. climate zones. In this study, we are describing present day conditions in terms of data regarding manufacturing and operations emissions as well as electricity and equipment costs and then going through the steps of taking a point-in-time decision on whether to retrofit or not. The two equipment we are taking into consideration are light bulbs in the lighting system and heat pumps in the HVAC system, assuming that they determine electricity consumption to a great deal. This study takes into consideration some of the major physical characteristics of the 10 case study buildings as well as their geographic location and associated climate conditions.

Due to the limited time, this report covers only two scenarios -

LIGHTING - When the fluorescent light bulbs have reached end of life and no longer work

- Option 1 - replace with same fluorescent light bulbs
- Option 2 - replace with new LED bulbs

HVAC - When the heat pumps have reached the end of life but are still being used inefficiently (consuming more electricity)

- Option 1 - continue using the outdated heat pumps
- Option 2 - replace with new heat pumps

The intended audience are primarily private warehouse owners who may be aware of the best retrofit strategies out there, but struggle to decide whether the upgrade would be worth it. We also see this work as fitting into analyses on environmental efficiency of supply chains.

By using eQuest (software), we were able to find -

- The peak heating and cooling load will be essential for determining a recommended heating and cooling system for the space.
- The yearly energy used for heating and cooling is important for determining the operating costs associated with the current HVAC system.

The process of determining a new recommended system is done by devising a list of water source heat pump that are considered the best within its capacity range. The factors considered in determining the optimal heating and cooling system includes cost, Energy Efficiency Ratio (EER), and Coefficient of Performance (COP). The capacity ranges will span 6,000Btu/hr to 420,000Btu/hr,

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[1] CBRE Research Shows Many U.S. Warehouses Are under-Equipped to Meet e-Commerce Demands." Accessed October 24, 2018. https://www.mmh.com/article/cbre_research_shows_many_u.s._warehouses_are_under_equipped_to_meet_e_comme.

[2] Bureau of Labor Statistics Data. (n.d.). Retrieved December 5, 2018, from https://data.bls.gov/timeseries/ENUUS000205493?amp%253bdata_tool=XGtable&output_view=data&include_graphs=true

[3] https://smartech.gatech.edu/bitstream/handle/1853/58711/FENG-THESIS-2017.pdf?sequence=1&isAllowed=y

Introduction

As we can see from see from Fig. 1 (in the Appendix) the total energy consumed by the industrial sector is greater than other types of buildings. A major chunk of this energy is attributed to the electricity consumption. HVAC and lighting fall under these building services and hence account for a major portion out of the electricity consumed. The objective of our project is to provide users a quick and simple answer on whether it will be worth it to retrofit their HVAC heating and cooling systems and their lighting systems and which technology in the future will provide this optimal retrofit strategy. The methods used require the owners to have information about the dimensions of their facility, the current electricity consumption for HVAC and lighting, the location, and if possible, the insulation type used for the construction of the building. We referred to CBRE's research on the leasing activity for Industry+Logistics markets as well as the different climate zones in the US, while selecting our 10 case study warehouses -

Warehouse List (10)	**Address**
Prologis Fremont	48366 Milmont Ave
Prologis Kaiser Distribution Center	13048 Valley Blvd.
Prologis Battleground	2902 E 13th St, Deer Park, Texas
Prologis Aurora	2640 White Oak Cir, Aurora, Illinois
Prologis Park 100 21	5801 W. 82nd St., Indianapolis Indiana 46278
Prologis Davenport Distribution Center	2314 Waverly Barn Road, Davenport, FL
Harrisburg 7	1530 Bobali Drive, Harrisburg Pennsylvania 17104
Lehigh Valley East 8	2685 Brodhead Rd, Bethlehem Pennsylvania 18020
Prologis Royal 85 Industrial 3605	3605 Royal S Pkwy, Atlanta Georgia 30349
Pagosa Dist Ctr 01	3150 Pagosa Street, Aurora Colorado 80011

Table 1: List of warehouses selected for study

We relied on various sources for data and assessed the quality of our data set in a pedigree matrix (see Fig 3. In Appendix), variable by variable -

Data Type	Data Source
Old HVAC equipment (only Heat Pump) specifications	ENERGY STAR® Program Requirements for Light Commercial HVAC - Eligibility Criteria (Retrieved 12/2/2018)
New HVAC equipment (only Heat Pump) specifications	Daikin Report
Old Lighting equipment (only Bulb) specifications	Phillips Report
New Lighting equipment (only Bulb) specifications	Phillips Report
HVAC cost (New only)	Official Reseller (only for California) from manufacturer's website
Lighting Cost (New only)	Amazon (retrieved 12/2/2018)
Manufacturing emissions of HVAC (only Heat Pump)	Research paper (2017)
Manufacturing emissions of Lighting (only Bulb)	Department of Energy (DoE) Report

Table 2:

In terms of energy efficiency, US EPA's Energy Star Portfolio Manager does model Energy Use Intensity (EUI) for warehouse and storage buildings as shown in fig 2 (Appendix). It is mentioned that source energy is the most equitable way to combine primary and secondary energy types so that the warehouses don't get penalized or credited for the energy sources of utility companies. Therefore, we have also taking the electricity mix of the different regions into consideration.

Problem Statement

Our larger questions are -

- How shall we evaluate the efficiency of current heat pumps and bulbs in these 10 warehouses?
    - Are current systems designed for peak loads and thus are underutilized most of the time?
- When would it be worth it to replace them with newer, more efficient equipment?
    - What technology advancement is worth of changing the entire existing system and at what cost? Will a small increase in efficiency be enough to make the change?
    - How will the cost of new technologies affect the decision of retrofitting the mentioned systems? What cost will make a technology feasible for retrofitting?

Questions to Answer

Due to the limited time, this report covers only two scenarios -

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- Option 1 - replace with same fluorescent light bulbs
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HVAC - When the heat pumps have reached the end of life but are still being used inefficiently (consuming more electricity)

- Option 1 - continue using the outdated heat pumps
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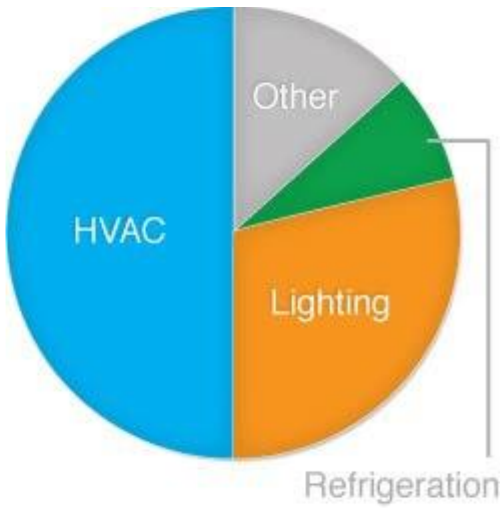
Background

For the optimization of the buildings energy consumption the monitoring and analysis of the various energy consumption systems are a key element. Out of these space heating, space cooling and lighting account for a major portion as can be from Fig. 1. These utilities have remained the pivotal elements for the renovation strategies as they allow the identification and correction of inefficient energy usage. However, according to a study by Dhooma et al. (2012) warehouses which are an integral part of the supply chain have not been analyzed as extensively for energy construction as have the rest of the components. It was observed that even where different warehouse networks or supply chain structures have been examined, it is the transport links that have been the focus of research (e.g. Browne et al. 2006, Kohn and Huge-Brodin 2008).

Fig. 1 Warehouse Energy Consumption



Source: http://www.iliveinthebayarea.com/leed/property-solutions/warehouse-dc/, Accessed at: 10/04/2018, 15:00

For most warehouses the strategy has been to perform an energy audit which involves the measurement of the base energy consumption, possibly how much an individual component consumes energy, and then the identification of improvement possibilities. Such audits have been developed by Konopacki and Akbari (1996), Capehart et al. (2004), Barley et al. (2005) and the Carbon Trust (2008b). These audits however are also focused on the building and are not specifically for warehouses.

Even after the identification of such opportunities there is a fear of the cost implication of such environmental initiatives (O'Brien 1999). However, retrofitting of existing buildings offers significant opportunities for reducing the energy consumed and greenhouse gas emissions both directly through better technology and indirectly as the reduction of energy. Hence this should be considered as a viable approach to achieving sustainability in the built environment at relatively low cost and high uptake rates. Although there are a wide range of retrofit technologies readily available, methods to identify the most cost-effective retrofit measures for particular projects is still a major technical challenge Ma et al (2012).

Another study by Roth (2002), which was conducted under all 8 U.S. climate zones and typical building types aimed at drawing a more comprehensive understanding of the energy performance of a project when it is designed under a different environment. The warehouses analyzed were also inspired by this study. The study also performed a comprehensive comparison of multiple energy saving measures was conducted to rank the energy saving potentials of various parameters, including HVAC system, cooling EER, heating COP, lighting power density, window U-value window and roof R-value, in a building energy simulation-based model for different building types and climates. Since the research had a consistent simulation engine, input, and professional perspective from consulting industry, the research was able to analyze the energy usage from the comprehensive composition with consistent and comparative measures. This study was performed during the design stage and hence the same factors were used to determine the viability of retrofit strategies in the use phase of buildings.

The studies however all focused on identifying the current best plan of action taking into consideration what technologies currently exist and finding the best solution for a retrofit. Such a retrofit may not always be optimal considering the time these investments take to break even on the investment. This then calls the need for a model which can audit the current energy use and propose a strategy whether technology is viable for replacement considering the economic and environmental implications of the retrofit.

The operating data for the different systems was taken from their respective websites, but however data relating to the manufacturing emissions of both lighting and HVAC was limited and diverse and the one most closely representative of the system being considered in our study was considered. A pedigree matrix is also included in the study so that the quality of data can be ascertained.

Type of data	Acquistion method	Independence of data supplier	Representitiveness	Temporal correlation	Geographical correlation	Further technological correlation
HVAC spec. old	4	1	NA	1	2	3
HVAC spec. new	4	1	NA	1	2	3
Lighting Spec.	4	1	NA	1	2	3
Electricty mix	3	1	1	1	1	1
HVAC cost (New	4	2	5	1	3	1
Lighting Cost (Ne	5	4	1	1	1	1
Manufacturing e	2	2	5	2	4	2
Manufacturing e	2	2	5	1	2	2

Methodology

Modeling Approach and Data (discussion of assumptions, models and methods, data sources):

As the e-commerce trade revitalizes the warehousing industry, there is an ever-growing problem of bringing warehouses of the past to today's energy standards. One of a building's biggest energy users are a building's HVAC and Lighting systems. The objective of our project is to provide users a quick and simple answer answer on whether it will be worth it to retrofit their HVAC heating and cooling systems and their lighting systems.

HVAC:

In our approach for HVAC, we will be conducting an analysis of the heating and cooling systems used in a building. We started the analysis by using the software eQuest to find a preliminary estimate of the performance of the current systems. Users have the option to input a multitude of variables that will help model the peak load demand and yearly energy usage for heating and cooling. Some of the main variables include building dimensions, location, building materials, building orientation, window size and orientation, and current system capacity and its EER and COP. To gather the required information, a questionnaire was developed where users can input the variables we need. The user also has the option to not input information for variables they do not know. For the variables that were not filled, we would estimate the values through using what is generally used in the timeframe from which the facility was built or last retrofitted. A sample questionnaire is attached on page X of appendix X.

From the information gathered in the questionnaire, we run a building energy simulation through eQuest to get the peak heating and cooling load required, and the current yearly energy use for heating and cooling. The peak heating and cooling load will be essential for determining a recommended heating and cooling system for the space. The yearly energy used for heating and cooling is important for determining the operating costs and emissions associated with the current HVAC system.

The process of determining a new recommended system is done by devising a list of water source heat pump that we feel are the best within its capacity range. Table X shows the heat pumps that we will be recommending. The factors considered in determining the optimal heating and cooling system includes cost, Energy Efficiency Ratio (EER), and Coefficient of Performance (COP). The capacity ranges will span 6,000Btu/hr to 420,000Btu/hr. Table X shows the recommended systems per capacity range. More details on the specifics of which heat pumps are chosen is written in appendix X.

Table X. Recommended Heat Pumps for corresponding system capacity ranges.

Capacity Range (Btu/hr)	Recommended Heat Pump
6,000 - 72,000	Daikin SmartSource High Efficiency Horizontal and Vertical Water Source Heat Pumps

72,000 - 300,000	Daikin Enfinity Vertical Floor Mounted Water Source Heat Pumps
300,000 - 420,000	Daikin Rooftop Outdoor Curb Mounted Water Source Heat Pumps

To obtain the values of the yearly cooling and heating load through using the new heat pumps, the energy simulation is run again through eQuest with the new system. With the new yearly cooling and heating load, we will perform an assessment of the life cycle emissions and Life Cycle Cost Analysis (LCCA) of the new heat pump. We will also calculate the emissions and operating costs of the current heating and cooling systems. However, since the heating and cooling system is old, we have taken into account the loss of efficiency. We have assumed the heat pump emissions will increase 3% for every year it has been commissioned. Thus, the operating emissions will be calculated as follows:

$$Operating\ Emissions = (Heating\ and\ Cooling\ Emissions\ from\ eQuest) \times 1.03^{\ years\ commissioned}$$

For the calculations of life cycle emissions of the new heat pump, scrapping emissions will be ignored as not all heat pumps are recycled and the values will be miniscule compared to the other emissions. For the LCCA of the new heat pump, a 3% discount rate is assumed. In our project, we also assumed that the heating and cooling systems will maintain its performance over the years. To calculate the number of years for the new heat pump to beat the current systems in terms of emissions, we divide the manufacturing emissions of the new heat pump with the difference in yearly operating emissions of the new heat pump and old system. To get the number of years required for the new system to be worth it economically, we use a discounted payback period formula.

$$Life\ Cycle\ Emissions\ of\ Heat\ Pump = Manufacturing\ Emissions + Operating\ Emissions$$

$$Years = \frac{Manufacturing\ Emissions\ of\ New\ Heat\ Pump}{Operating\ Emissions\ of\ System - Operating\ Emissions\ of\ New\ System}$$

$$Discounted\ Payback\ Period = \frac{ln\left(\frac{1}{1 - \frac{Heat\ Pump\ Price \times 0.03}{Yearly\ Savings\ of\ Operating\ Cost}}\right)}{ln(1.03)}$$

Lighting:

In our approach for the lighting of the warehouse, we gain information of the current lighting system through the same questionnaire. Information collected includes the number of light fixtures, the number of luminaires in the fixture, and its rating. From the information gathered in the questionnaire, we are able to calculate the current operating cost and emissions of the lights.

For the purposes of the lighting portion of our project, we will set Philips Mains T5 LEDtube luminaires as our recommended lights. This product was chosen due to its best-in-class efficiency and durability. More information of T5 luminaires will be found in appendix X. To get the number of T5 luminaires needed to satisfy the lighting requirements of a warehouse, we referenced the Illuminating Engineering Society standards which recommends an average maintained illuminance per square foot of 15FC. Through our analysis, we also calculated the operating costs and emissions for lighting the warehouse using the T5 luminaires. An analysis is then done to find the number of years it will take for the new system to be beneficial both economically and environmentally. If the number of years exceed the expected lifetime of the T5 luminaire, it will mean that the new lighting system will not be beneficial in that category.

<u>Energy to operate existing lighting system</u>
= (no. of lights)(no. Of luminaires/light)(Wattage of luminaire)(yearly hours of usage)

<u>No. of T5 luminaires needed</u> = (Floor Area)(15lm/ft^2)/(3,600lm/luminaire)

<u>Energy to operate new lighting system:</u>
= (No. T5 luminaire)(26W/luminaire)(yearly hours of usage)

<u>Operating Emissions</u> = (Operating energy)(GHG Emissions of electricity mix)

<u>Operating Costs</u> = (Operating energy)(Cost of electricity)

$$\underline{Years} = \frac{Manufacturing\ Emissions\ of\ T5\ Luminaire}{Operating\ Emission\ of\ Current\ lights\ -\ Operating\ Emission\ of\ New\ lights}$$

$$Discounted\ Payback\ Period\ = \frac{ln\left(\frac{1}{1-\frac{(LED\ Price - Flourescent\ Price)\times 0.03}{Yearly\ Savings\ of\ Operating\ Cost}}\right)}{ln(1.03)}$$

Interpretation and Discussion of Results

Results:

Table X. Warehouse Data with Electricity Mix and Price

Warehouse List	Location	Electricity Mix (gCO_2/kWh)	Electricity Price ($/kWh)
Prologis Fremont	Fremont, CA	362.357	0.155
Prologis Kaiser Distribution Center	Fontana, CA	362.357	0.155
Prologis Battleground	Deer Park, TX	765.67	0.0586
Prologis Aurora	Aurora, IL	558.73	0.0662
Prologis Park 100 21	Indianapolis, IN	784.77	0.0707
Prologis Davenport Distribution Center	Davenport, FL	812.84	0.0764
Harrisburg 7	Harrisburg, PA	602.64	0.0662
Lehigh Valley East 8	Bethlehem, PA	602.6412	0.0662
Prologis Royal 85 Industrial 3605	Atlanta, GA	739.5	0.0622
Pagosa Dist Ctr 01	Aurora, CO	754.0202	0.073

Unfortunately, we were unable to obtain any data from building owners regarding their warehouses. Thus, to test our methodology, our team have gathered information on several warehouses from all over the United States. Table X shows the location and address of the properties. These properties are all owned by Prologis, a large real estate company. We have gathered data about the building dimensions and heights from Prologis' website, and found the number of doors and facade the warehouse has through google maps. Since we were unable to procure data for the warehouses' actual current HVAC systems, we have assumed that all the HVAC systems for the warehouses meet the Energy Star requirement of 2003 for heat pump efficiency. These heat pumps has an EER value of 14.9 and a COP value of 5.3. Due to the size of the warehouses we have chosen, only the Daikin Rooftop Outdoor Curb Mounted Water Source Heat Pumps were used. The manufacturing emissions were assumed to be 975,610gCO_2/unit, which was gathered from XXX, and the price was found to be $40,000 before tax.

Since we were not able to gather any data from building owners, we have assumed for all our cases that the warehouses' current lighting system is fluorescent. We will be determining whether it is worth it to reuse the same lights compared to switching into LED. The fluorescent lighs we will be using is also be Philips, and is called the T5 Standard. Additional specifications for the lights are attached in appendix X

HVAC:

Table X. HVAC Assessment Results

Warehouse List	Current Operating Emissions (gCO2/yr)	Current Operating Cost ($)	New Operating Emissions (gCO2/yr)	New Operating Costs ($)	Number of New Heat Pumps Needed	Emission Years (Yr)	Cost Years (Yr)
Prologis Fremont	47,485,779.36	20,312.28	26,888,659.51	11,501.76	3	0.142	19.509
Prologis Kaiser Distribution Center	198,611,550.60	84,957.07	77,399,000.80	33,107.81	12	0.097	11.964
Prologis Battleground	527,598,112.99	40,379.34	206,091,642.12	15,773.07	7	0.021	15.606
Prologis Aurora	269,797,542.76	31,966.42	145,698,161.53	17,262.75	3	0.024	10.277
Prologis Park 100 21	266,624,627.53	24,020.37	140,983,556.67	12,701.29	2	0.016	8.612
Prologis Davenport Distribution Center	1,226,319,120.15	115,263.50	454,655,730.10	42,733.75	14	0.018	9.531
Harrisburg 7	383,064,187.25	42,079.51	211,646,563.14	23,249.33	5	0.028	13.942
Lehigh Valley East 8	703,813,983.78	77,313.81	403,600,081.03	44,335.38	10	0.032	16.485
Prologis Royal 85 Industrial 3605	487,884,641.35	41,036.41	234,155,280.00	19,695.01	8	0.031	21.340
Pagosa Dist Ctr 01	606,093,344.72	58,678.55	348,615,351.33	33,750.98	6	0.023	11.932

With the data gathered through the various sources, we were able to run our assessment to calculate the number of years it will take for the new heat pump to be superior emissions and cost. Table X shows the main outputs of our model.

From our results, we can see that the number of years it takes for the retrofit to be worth it emissions wise. This is because as expected, the operating emissions of a HVAC system is much larger than the manufacturing emissions of a heat pump. However, the initial investment of $40,000 per heat pump is extremely large. From our results, we can see that in all but one case, it will be worth it to retrofit even in terms of cost, as the new heat pump will have a life-span of about 20yrs.

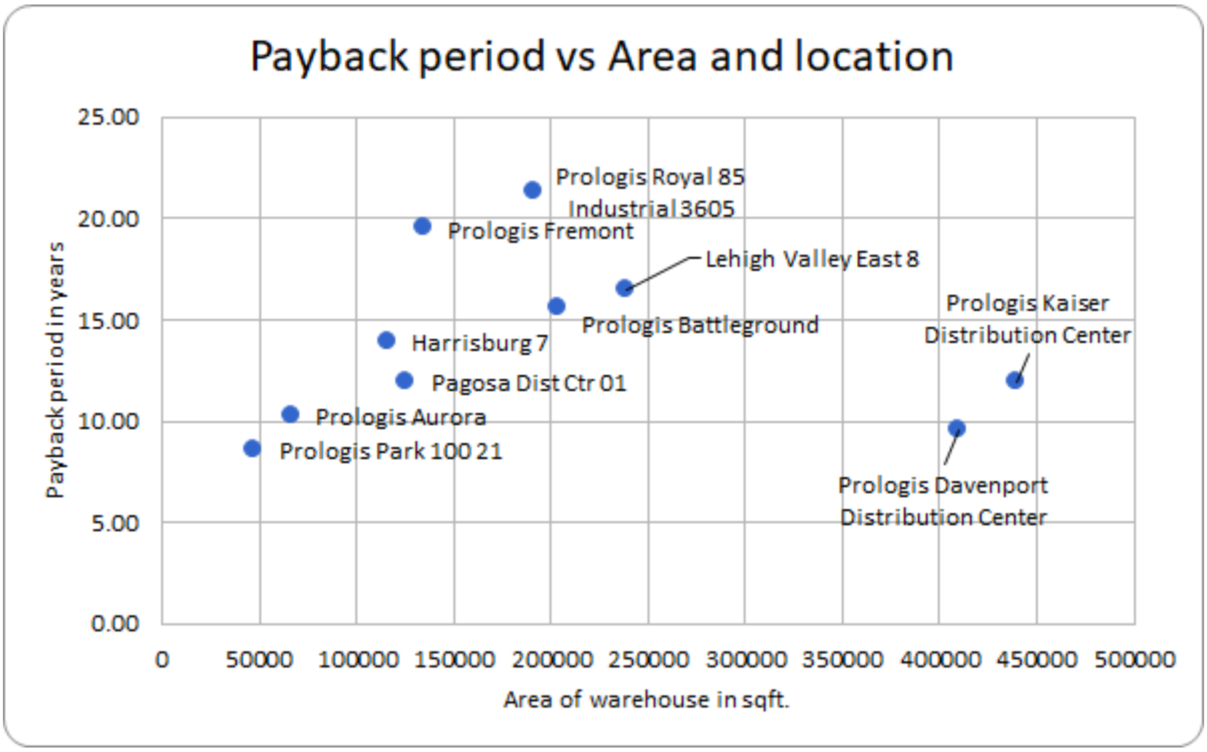


Figure X. Payback Period vs. Location

Figure X shows the payback period of the HVAC system with respect to the area of the location. Though it is evident that it is worth it to retrofit when looking at emissions, it is not so clear in terms of cost. Furthermore, there is no clear reason why some properties take longer to pay back compared to others. Upon further analysis, some trends could be interpreted. First, we found that the larger the area, the larger the payback period. Also, the emissions of cooling has drastically decreased over the past 15 years. On the other hand, The emissions of heating has improved, but not as drastically. Thus, the payback period for places with hotter weather will be lower than that of colder places. Thus, that explains why a large warehouse in Florida has approximately the same payback period as a small warehouse in Illinois.

Lighting:

Table X. Lighting Results Table

Warehouse List	**Number of LED Needed**	**Number of CFL Luminaires**	**Current Operating Emissions (gCO2/yr)**	**Current Operating Cost ($)**	**New Operating Emissions (gCO2/yr)**	**New Operating Costs ($)**	**Emission Years (Yr)**	**Cost Years (Yr)**
Prologis Fremont	561	1682	33,366,795.07	14,272.81	19,291,488.09	8,252.03	-0.576	1.886
Prologis Kaiser Distribution Center	1834	5500	109,114,751.63	46,674.38	63,067,003.84	26,977.22	-0.576	1.885
Prologis Battleground	850	2550	106,897,102.88	8,181.29	61,762,770.55	4,726.97	-0.273	5.282
Prologis Aurora	277	830	25,390,088.03	3,008.29	14,687,503.13	1,740.22	-0.374	4.555
Prologis Park 100 21	199	595	25,564,723.63	2,303.14	14,820,378.72	1,335.18	-0.266	4.301

Prologis Davenport Distribution Center	1709	5125	228,077,823.75	21,437.36	131,829,723.84	12,390.87	-0.257	3.892
Harrisburg 7	486	1457	48,069,016.18	5,280.37	27,794,655.84	3,053.24	-0.346	4.538
Lehigh Valley East 8	995	2984	98,447,654.76	10,814.45	56,904,696.63	6,250.97	-0.346	4.534
Prologis Royal 85 Industrial 3605	798	2393	96,866,642.81	8,147.54	56,002,482.90	4,710.42	-0.282	4.752
Pagosa Dist Ctr 01	521	1562	64,478,270.17	6,242.42	37,280,945.35	3,609.33	-0.277	3.961

As with the HVAC system, it is definitely worth it to change into an LED system when considering emissions when looking at the results we have gotten from table X. In our analysis, we assumed a manufacturing emission of 12,500gCO2/luminaire for the LED strip, and 8,990gCO2/luminaire for the fluorescent light strip. Though an LED luminaire has a higher manufacturing emission, its luminosity or amount of light is also greater than the fluorescent lights. When comparing the manufacturing emissions per unit of light, we find that LED light has a manufacturing emission of 3.47gCO2/lm while the fluorescent light strip has an emission of 7.49gCO2/lm. Because of that, overall manufacturing emission of an LED system will be lower than that of a fluorescent system. Thus, the years it will take for the LED system to be worth it emissions wise is negative, which means that right off the bat, the LED system is better in terms of emissions than a fluorescent system.

Sensitivity analysis

Sensitivity analysis was conducted on the factors affecting the total cost of the electric consumption and the total cost saved by the new system. Here we observed that our results are dependent on many variables. Among these, the cost of the electricity is found to be of very high influence. The following graphs show the change of the payback period in years with the change in the cost of electricity, for the HVAC and Lighting systems respectively.

With the California wildfires raising the prices of electricity in November 2018, the price of electricity increased. With the global temperatures rising analogously the price of electricity is expected to rise and hence considering this fact a sensitivity analysis was performed with respect to the electricity prices.

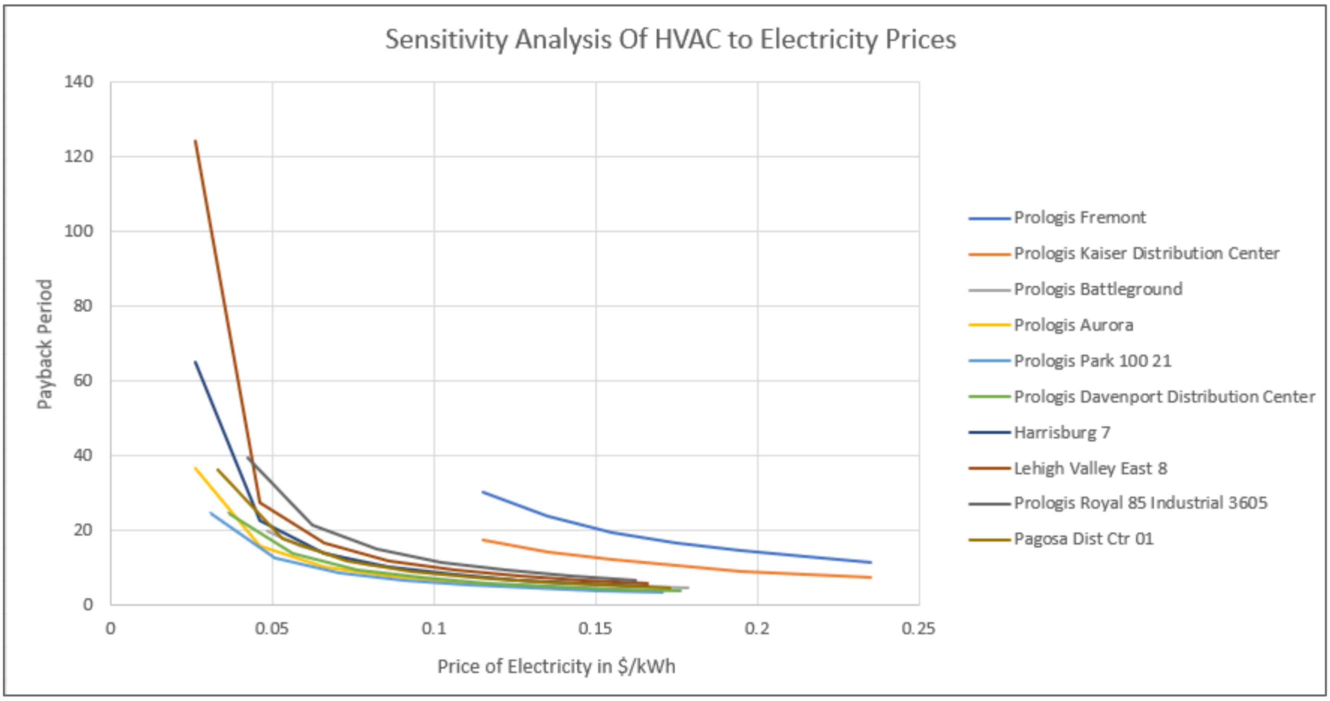


Figure X: Graph showing the change in the payback period of the HVAC system due to change in the electricity cost

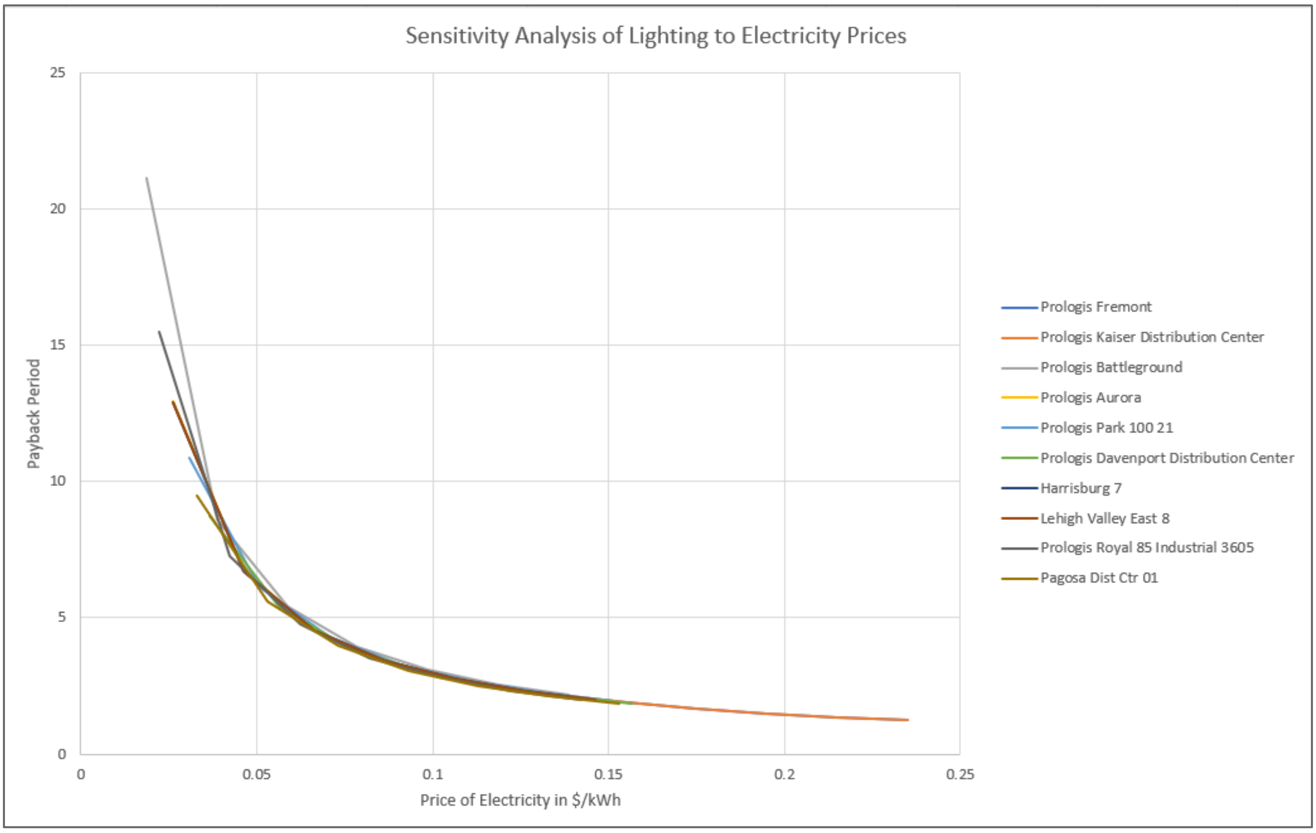


Figure X: Graph showing the change in the payback period of the Lighting system due to change in the electricity cost

The above graphs show that the payback period decreases as the electricity cost increases. This is observed as the increase in electricity prices show that there is an increase in the amount of savings and hence the payback period is reduced. Thus, we can see a high sensitivity to electricity prices with a change of 2 cents resulting in almost 5 year change in the payback period for the retrofit.

If the electricity prices decrease however, the old system becomes relatively better as the savings made are not as much and hence would take longer for the new system to break even.Thus a decrease in energy prices would result in a higher payback period as a result of these decreased savings.

Uncertainty Analysis

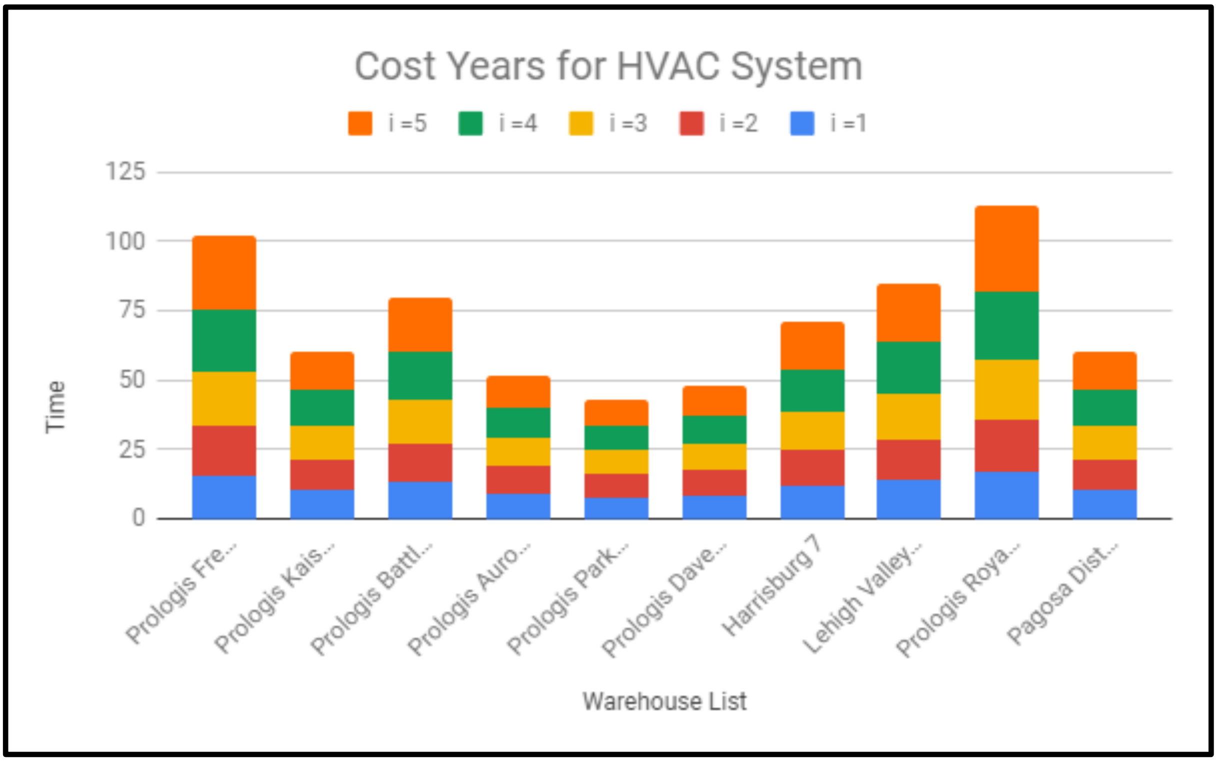
Uncertainty analysis was run on several of our assumptions

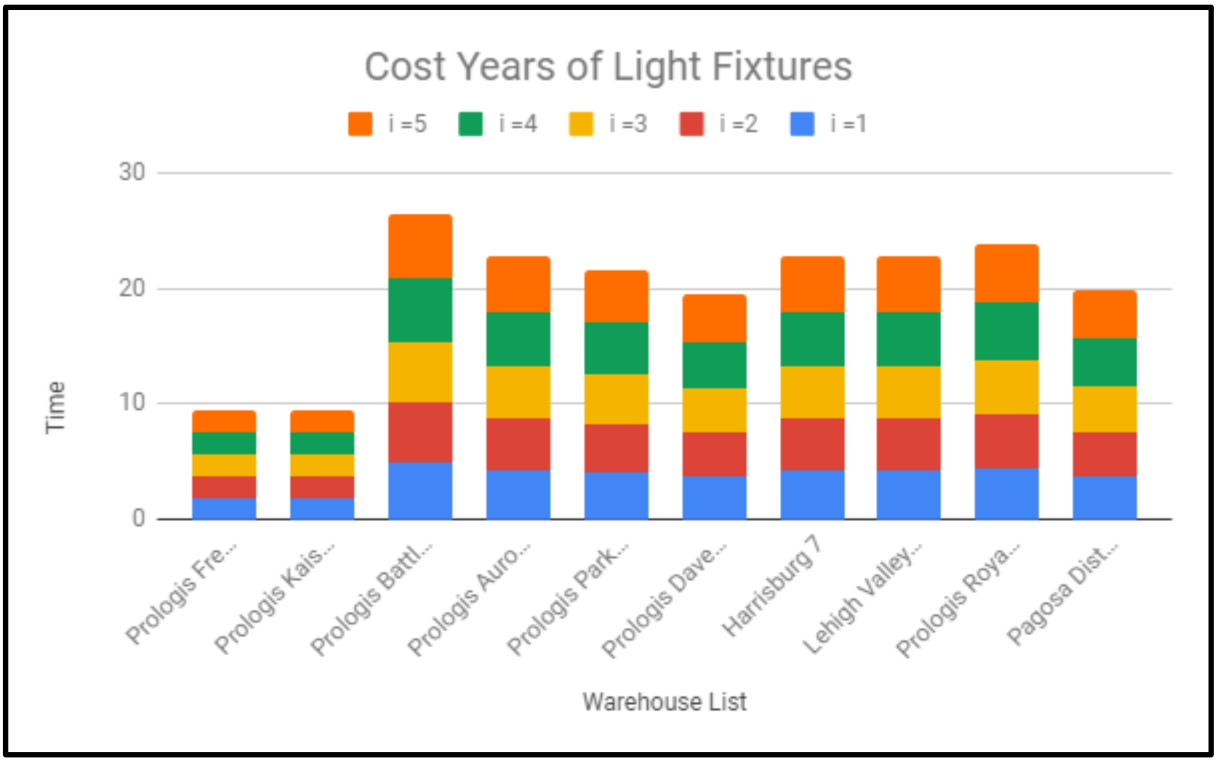
1. Changing the discount rate

Assumption: In the calculations section, the discount rate was assumed to be 3%.
To check how the results, change with the change of discount rate, the calculation where done again with for a discount rate equal to 1, 2, 3, 4 and 5 %
Results:

HVAC	i =1	i =2	i =3	i =4	i =5
Warehouse List	Cost Years	Cost Years	Cost Years	Cost Years	Cost Years
Prologis Fremont	15.870060	17.448398	19.508770	22.380904	26.864638
Prologis Kaiser Distribution Center	10.509148	11.178549	11.963520	12.903613	14.061245
Prologis Battleground	13.210974	14.282979	15.606370	17.304434	19.611585
Prologis Aurora	9.183173	9.693064	10.277082	10.956139	11.760798
Prologis Park 100 21	7.826136	8.197168	8.612459	9.082067	9.619684
Prologis Davenport Distribution Center	8.581231	9.026550	9.531359	10.110947	10.786949
Harrisburg 7	12.003896	12.882739	13.942395	15.258689	16.963512
Lehigh Valley East 8	13.830541	15.010366	16.485198	18.411542	21.102283
Prologis Royal 85 Industrial 3605	17.037917	18.876032	21.339812	24.924048	31.006009
Pagosa Dist Ctr 01	10.484962	11.151237	11.932198	12.866964	14.017174

Light	i =1	i =2	i =3	i =4	i =5
Warehouse List	Cost Years	Cost Years	Cost Years	Cost Years	Cost Years
Prologis Fremont	1.833427	1.859623	1.886392	1.913759	1.941750
Prologis Kaiser Distribution Center	1.832090	1.858254	1.884990	1.912322	1.940278
Prologis Battleground	4.963234	5.117396	5.282270	5.459240	5.649958
Prologis Aurora	4.310680	4.429106	4.554522	4.687693	4.829510
Prologis Park 100 21	4.080999	4.188009	4.300948	4.420426	4.547146
Prologis Davenport Distribution Center	3.708139	3.797888	3.892089	3.991155	4.095552
Harrisburg 7	4.295816	4.413485	4.538072	4.670330	4.811138
Lehigh Valley East 8	4.292145	4.409628	4.534009	4.666043	4.806602
Prologis Royal 85 Industrial 3605	4.488536	4.616216	4.751792	4.896170	5.050413
Pagosa Dist Ctr 01	3.771478	3.864049	3.961303	4.063681	4.171685





As expected, the number of years it takes for replacing the system to be worth it increases with the increase of discount rate. It is worth to note that the change of cost years for the lightings system was relatively small with increasing the discount rate, while the change of cost years for the HVAC system was much larger. That is mainly because the initial investment for installing the HVAC system is much more costly than installing the lighting.

2. Changing the manufacturing emissions

We assumed the emissions due to manufacturing of the lighting fixtures and heat pumps by using numbers from other researches on similar products.

To check how the results change with the change of manufacturing emissions, the calculation where done again by increasing and decreasing these emissions by 10, 20, 30, 40 and 50 %.
Results:

	Emission Years				
HVAC	Decrease				
Warehouse List	50%	40%	30%	20%	10%
Prologis Fremont	0.071049	0.085259	0.099469	0.113679	0.127889
Prologis Kaiser Distribution Center	0.048293	0.057951	0.067610	0.077268	0.086927
Prologis Battleground	0.010621	0.012745	0.014869	0.016993	0.019117
Prologis Aurora	0.011792	0.014151	0.016509	0.018868	0.021226
Prologis Park 100 21	0.007765	0.009318	0.010871	0.012424	0.013977
Prologis Davenport Distribution Center	0.008850	0.010620	0.012390	0.014160	0.015930
Harrisburg 7	0.014229	0.017074	0.019920	0.022766	0.025611
Lehigh Valley East 8	0.016249	0.019498	0.022748	0.025998	0.029247
Prologis Royal 85 Industrial 3605	0.015380	0.018456	0.021532	0.024609	0.027685
Pagosa Dist Ctr 01	0.011367	0.013641	0.015914	0.018188	0.020461

	Emission Years				
HVAC	Increase				
Warehouse List	10%	20%	30%	40%	50%
Prologis Fremont	0.156309	0.170519	0.184729	0.198939	0.213148
Prologis Kaiser Distribution Center	0.106244	0.115902	0.125561	0.135219	0.144878
Prologis Battleground	0.023366	0.025490	0.027614	0.029738	0.031862
Prologis Aurora	0.025943	0.028301	0.030660	0.033018	0.035377
Prologis Park 100 21	0.017083	0.018636	0.020189	0.021742	0.023295
Prologis Davenport Distribution Center	0.019470	0.021240	0.023010	0.024780	0.026550
Harrisburg 7	0.031303	0.034149	0.036994	0.039840	0.042686
Lehigh Valley East 8	0.035747	0.038997	0.042246	0.045496	0.048746
Prologis Royal 85 Industrial 3605	0.033837	0.036913	0.039989	0.043065	0.046141
Pagosa Dist Ctr 01	0.025008	0.027282	0.029555	0.031828	0.034102

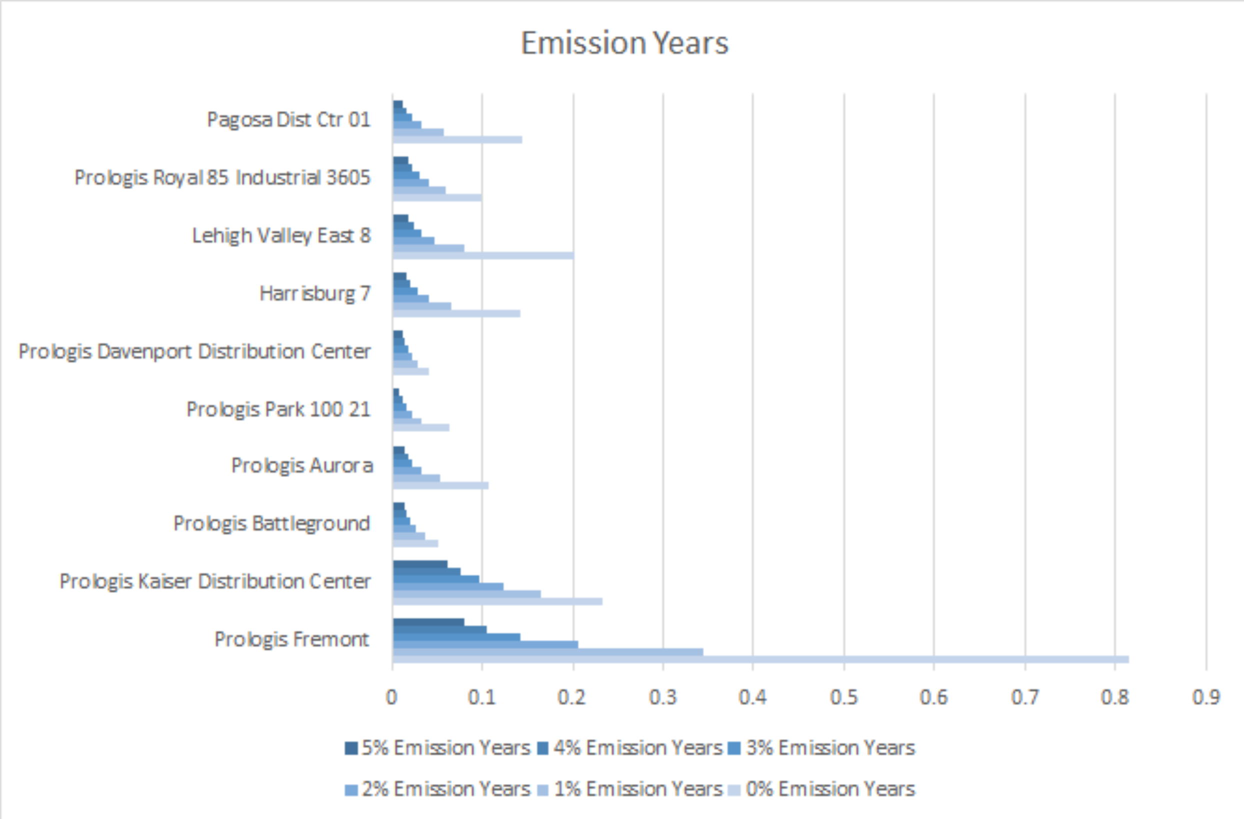
	Emission Years				
Light	Decrease				
Warehouse List	50%	40%	30%	20%	10%
Prologis Fremont	-0.03890	-0.14632	-0.25375	-0.36117	-0.468590
Prologis Kaiser Distribution Center	-0.03904	-0.14641	-0.25379	-0.36117	-0.468546
Prologis Battleground	-0.01855	-0.06934	-0.12013	-0.17093	-0.221717
Prologis Aurora	-0.02507	-0.09479	-0.16451	-0.23423	-0.303948
Prologis Park 100 21	-0.01741	-0.06719	-0.11698	-0.16676	-0.216546
Prologis Davenport Distribution Center	-0.01740	-0.06527	-0.11314	-0.16101	-0.208876
Harrisburg 7	-0.02336	-0.08796	-0.15256	-0.21716	-0.281764
Lehigh Valley East 8	-0.02346	-0.08803	-0.15259	-0.21716	-0.281733
Prologis Royal 85 Industrial 3605	-0.01907	-0.07170	-0.12434	-0.17697	-0.229607
Pagosa Dist Ctr 01	-0.01868	-0.07031	-0.12194	-0.17357	-0.225192

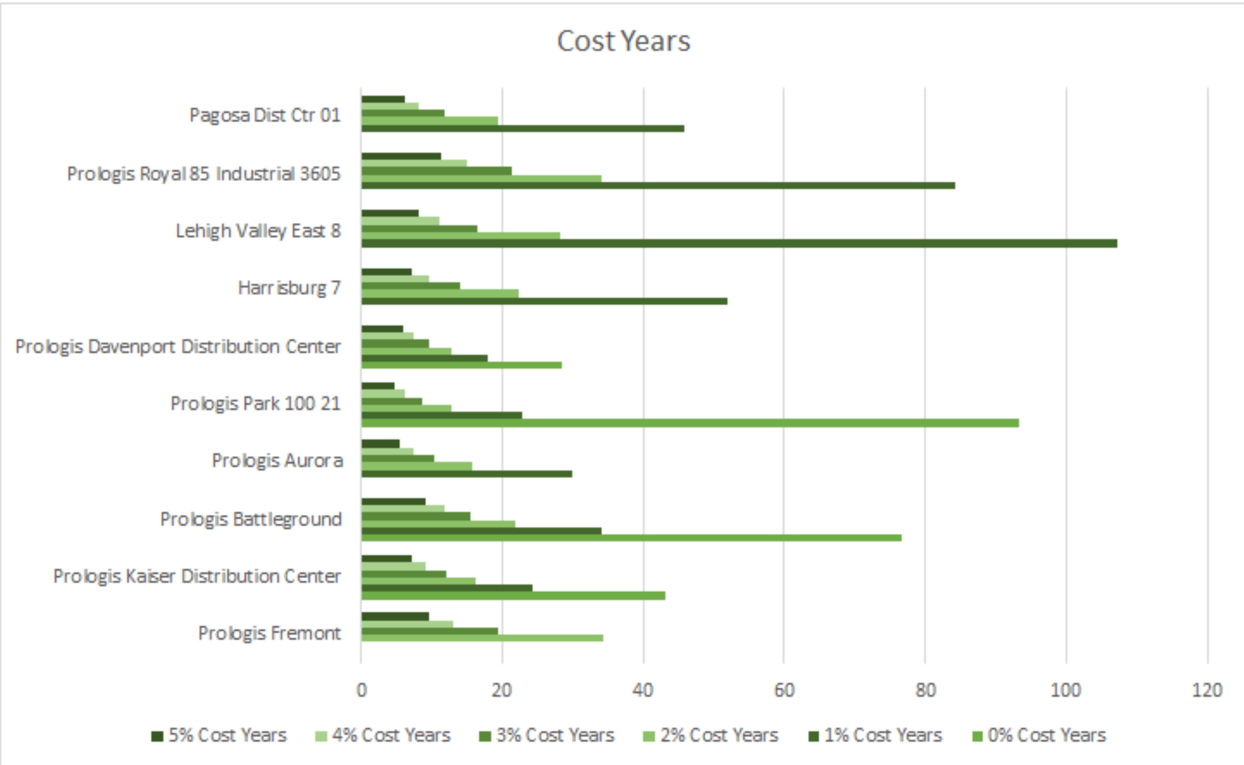
	Emission Years				
HVAC	Increase				
Warehouse List	10%	20%	30%	40%	50%
Prologis Fremont	-0.68344	-0.79086	-0.89828	-1.00570	-1.11313
Prologis Kaiser Distribution Center	-0.68330	-0.79068	-0.89806	-1.00543	-1.11281
Prologis Battleground	-0.32330	-0.37409	-0.42488	-0.47568	-0.52647
Prologis Aurora	-0.44339	-0.51310	-0.58282	-0.65254	-0.72226
Prologis Park 100 21	-0.31612	-0.36590	-0.41569	-0.46547	-0.51525
Prologis Davenport Distribution Center	-0.30462	-0.35248	-0.40035	-0.44822	-0.49609
Harrisburg 7	-0.41096	-0.47556	-0.54016	-0.60477	-0.66937
Lehigh Valley East 8	-0.41087	-0.47544	-0.54001	-0.60458	-0.66915
Prologis Royal 85 Industrial 3605	-0.33488	-0.38751	-0.44014	-0.49278	-0.54541
Pagosa Dist Ctr 01	-0.32845	-0.38007	-0.43170	-0.48333	-0.53496

3. System efficiency change

We assumed that the current HVAC system's efficiency decreases by 3% every year. To check how the results change with the decrease of efficiency of the current system over the years, the calculation where done again with for no loss in emissions (0%), 1, 2, 3, 4 and 5% loss of efficiency over the life of the existing system.

Results:





As expected, the Cost and Emission years increased as we decreased the discounting of efficiency of the current system. That makes sense because the lower the efficiency of the current the system, the more it becomes worth it to replace the system.

Conclusions and Recommendations

- The scope of this report was limited due to lack of high-quality datasets for analysis. There is a need to set a baseline based on warehouse sizes, the climate zones and energy mix. Warehouses can then be categorized and ranked to help regulators and owners assess their energy efficiency and associated global warming potential.
- Survey should be conducted to understand other possible options that owners may get to choose from with respect to In addition, there is need for further research that includes manufacturing and operation emissions of lighting and duct layouts as well as the cost-benefit analyses of improving them.
- With respect to methodology, since this study has relied on one software (EQuest), there is a need for calculating the same values using other manual methods of software in order to triangulate the results.

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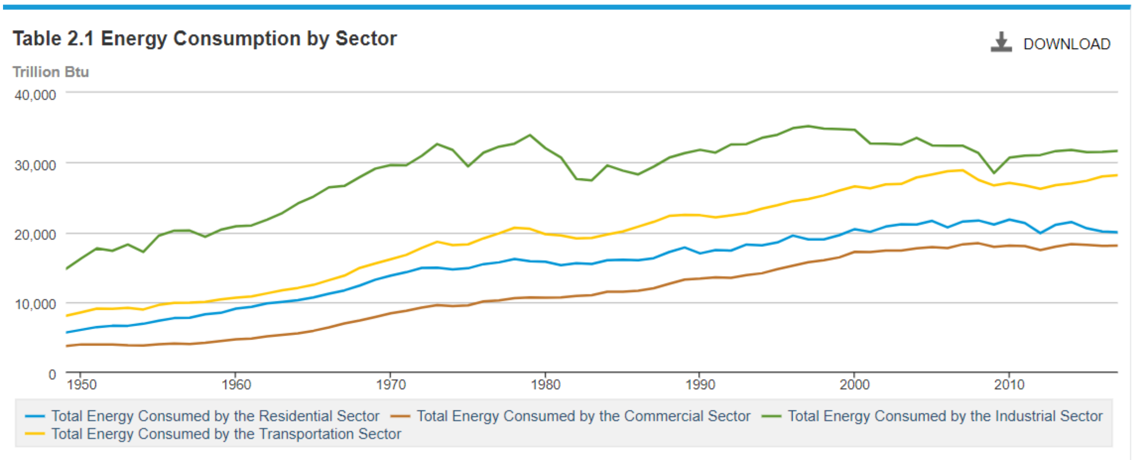
Appendix:

Fig 1. Total Energy consumption by sector in the United States



Source: https://www.eia.gov/totalenergy/data/browser/?tbl=T02.01#/?f=A&start=1949&end=2017&charted=3-6-9-12, Accessed 10/24/2018, 19:40

Fig 2: U.S. National Median Reference Values for All Portfolio Manager Property Types

Broad Category	Primary Function	Further Breakdown (where needed)	Source EUI (kBtu/ft²)	Site EUI (kBtu/ft²)	Reference Data Source - Peer Group Comparison
	Other - Utility		89.3	40.1	CBECS - Other
Warehouse/Storage	Self-Storage Facility		47.8	20.2	CBECS – Non-refrigerated Warehouse
	Warehouse/Distribution Center	Distribution Center*	52.9	22.7	CBECS – Non-refrigerated Warehouse & Distribution Center
		Non-Refrigerated Warehouse*			
		Refrigerated Warehouse*	235.6	84.1	CBECS – Refrigerated Warehouses

Source: “US Energy Use Intensity by Property Type,” 2018, 6.

Fig 3: Pedigree Matrix for Data collected

Type of data	Acquisition method	Independence of data supplier	Represen tativeness	Temporal correlation	Geographical correlation	Further technological correlation
HVAC spec. old	4	1	NA	1	2	3
HVAC spec. new	4	1	NA	1	2	3
Lighting Spec.	4	1	NA	1	2	3
Electricity mix	3	1	1	1	1	1

HVAC cost (New only)	4	2	5	1	3	1
Lighting Cost (New only)	5	4	1	1	1	1
Manufacturing emissions of HVAC	2	2	5	2	4	2
Manufacturing emissions of Lighting	2	2	5	1	2	2

Heat Pump Selection:

For the scope of our project, we will partner with Daikin, a world leader in HVAC technologies. The three product lines that we will use are the SmartSource Vertical Water Source Heat Pump, the Enfinity Vertical Floor Mounted Heat Pump, and the Rooftop Outdoor Curb Mounted Water Source Heat Pumps. Each of these three product lines has numerous sizes that depends on the air flow needed to heat and cool the space. According to ASHRAE Standard 62.1, a minimum of 0.06CFM/sf is needed in warehouse properties. Thus, the product line that is chosen will depend on the heating and cooling capacity needed, and the size of the heat pump is determined by the CFM needed for the space.

SmartSource® High Efficiency Horizontal and Vertical Water Source Heat Pumps	Single Stage	CFM	water	
	size		EER (cooling)	COP (heating)
	7	250	15.4	5.5
	9	300	15.6	4.8
	12	400	15.5	5.4
	15	500	18.1	5.9

	19	600	15.7	5.7
	24	800	16.9	6
	30	1000	17.3	5.8
	36	1250	19.2	6
	42	1400	17.5	5.4
	48	1600	17.2	5.4
	60	2000	17.4	5.2
	70	2160	15.9	5

Enfinity® Vertical Floor Mounted Water Source Heat Pumps	PSC fan motor size	CFM	Water loop	
			EER (cooling)	COP (heating)
	9	250	14	4.7
	12	300	14.4	4.8
	15	400	16	5.1
	19	500	15.2	4.4
	24	600	15.1	4.9
	30	800	17	5.2
	36	1000	14.8	4.6
	42	1250	15	4.8
	48	1400	14.7	4.8
	60	1600	15.1	4.7
	70	2000	13.5	4.4
	72	2300	13.1	4.6
	96	3600	13	4.7
	120	4000	14	5.3
	180	6000	14.9	4.9
	215	7167	14.2	4.9
	290	9670	11	4.1

Rooftop Outdoor Curb Mounted Water Source Heat Pumps	large	CFM	Water loop	
	size		EER (cooling)	COP (heating)
	150	5000	14.9	5.3
	200	6000	15.8	5.3
	240	8000	16.4	5.6
	300	10000	13.9	4.9
	420	12000	14.7	5

T5 Light Details:

Approval and Application	
Energy Consumption kWh/1000 h	26 kWh
Energy Efficiency Label (EEL)	A++
Controls and Dimming	
Dimmable	No
Operating and Electrical	
Input Frequency	50 to 60 Hz
Voltage (Nom)	220-240 V
Power (Rated) (Nom)	26 W
Starting Time (Nom)	0.5 s
General Information	
Cap-Base	G5
Nominal Lifetime (Nom)	50000 h
Rated Lifetime (Hours)	50000 h
Switching Cycle	200000X
Light Technical	
Beam Angle (Nom)	200 °
Color Rendering Index (Nom)	80
Lmf At End Of Nominal Lifetime (Nom)	70 %
Rated Beam Angle	200 °
Temperature	
T-Ambient (Max)	45 °C
T-Ambient (Min)	-20 °C
T-Storage (Max)	65 °C
T-Storage (Min)	-40 °C

Light Technical

Order Code	Full Product Name	Color Code	Correlated Color Temperature (Nom)	Luminous Flux (Nom)	Luminous Flux (Rated) (Nom)
929001908502	MAS LEDtube 1200mm HO 26W 830 T5	830	3000 K	3600 lm	3600 lm
929001908602	MAS LEDtube 1200mm HO 26W 840 T5	840	4000 K	3900 lm	3900 lm
929001908702	MAS LEDtube 1200mm HO 26W 865 T5	865	6500 K	3900 lm	3900 lm
929001908802	MAS LEDtube 1500mm HO 26W 830 T5	830	3000 K	3600 lm	3600 lm
929001908902	MAS LEDtube 1500mm HO 26W 840 T5	840	4000 K	3900 lm	3900 lm
929001909002	MAS LEDtube 1500mm HO 26W 865 T5	865	6500 K	3900 lm	3900 lm

Figure X: Detail specifications of the T5 LED luminaire by Philips

Philips, Light Technical, https://www.assets.lighting.philips.com/is/content/PhilipsLighting/comf7033830-pss-global, Accessed 10/22/2018 at 6:00pm

T5 Standard

14W/830 Min Bipin T5 HE ALTO UNP/40

Philips T5 Fluorescent Lamps featuring ALTO® Lamp Technology offer increased energy savings and low toxicity in a slim profile.

Product data

General Information	
Cap-Base	G5 [G5]
Life to 50% Failures Preheat (Nom)	24000 h
Features	HE Alto® [High Efficiency Alto]
System Description	High Efficiency
LSF Preheat 2000 h Rated	99 %
LSF Preheat 4000 h Rated	99 %
LSF Preheat 6000 h Rated	99 %
LSF Preheat 8000 h Rated	99 %
LSF Preheat 16000 h Rated	97 %
LSF Preheat 20000 h Rated	84 %

Light Technical	
Color Code	830 [CCT of 3000K]
Luminous Flux (Nom)	1350 lm
Luminous Flux (Rated) (Nom)	1200 lm
Color Designation	Warm White (WW)
Luminous Efficacy (@ Max Lumen, Rated) (Nom)	99 lm/W
Correlated Color Temperature (Nom)	3000 K
Luminous Efficacy (rated) (Nom)	86 lm/W
Color Rendering Index (Max)	85
Color Rendering Index (Min)	80
Color Rendering Index (Nom)	82
LLMF 2000 h Rated	96 %
LLMF 4000 h Rated	95 %
LLMF 6000 h Rated	94 %
LLMF 8000 h Rated	93 %
LLMF 12000 h Rated	92 %
LLMF 16000 h Rated	91 %
LLMF 20000 h Rated	90 %

Operating and Electrical	
Power (Rated) (Nom)	14.0 W
Lamp Current (Nom)	0.165 A

Temperature	
Design Temperature (Nom)	35 °C

Controls and Dimming	
Dimmable	Yes

Mechanical and Housing	
Cap-Base Information	Green Cap

Approval and Application	
Energy Efficiency Label (EEL)	A
Mercury (Hg) Content (Nom)	1.4 mg

Product Data	
Order product name	14W/830 Min Bipin T5 HE ALTO UNP/40

Figure X: Detail specifications of the T5 Fluorescent luminaire by Philips