Energy · Quality · Controllability℠

Choosing Both Energy Efficiency and Light Pollution Mitigation for Commercial Outdoor Lighting

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Executive Summary

The DLC is a nonprofit organization that provides decision makers with data and resources on quality lighting, controls, and integrated building systems to reduce energy consumption, carbon emissions, and light pollution. Collaborating with utilities, energy efficiency programs, manufacturers, lighting practitioners, building owners, and government entities, the DLC creates rigorous lighting performance criteria that keep pace with technology.

Amid growing awareness of light pollution's negative impacts on people, ecosystems, and the night sky, the DesignLights Consortium (DLC) created its LUNA program for outdoor LED products to mitigate the adverse effects of outdoor lighting. The DLC recently conducted a study with VH Lighting Services and Lighting Research Solutions to analyze the differences between LED fixtures that meet the LUNA Technical Requirements compared with DLC-qualified products that don't meet LUNA requirements. The study answers the question: What are the impacts on annual energy use, energy costs, and ROI if a city or town desires to use a retrofit solution that is both energy efficient and minimizes light pollution, rather than focusing on energy efficiency alone?

Many factors can impact light pollution, including light levels, color, fixtures, direction of light, BUG ratings, controls, and shields. Fixtures on the LUNA Qualified Products List (QPL) meet all the energy efficiency benchmarks of the DLC's Solid-State Lighting (SSL) Technical Requirements, plus additional criteria aimed at mitigating the unintended negative impacts of artificial light at night, including uplight control, light source color, shielding, and controllability.

To conduct this analysis, the research team investigated realistic outdoor lighting retrofit solutions that are energy efficient and minimize light pollution versus solutions focused on energy efficiency alone. The exterior grounds (parking lot) of a model high school and a main street in Fort Collins, Colorado served as application examples.

Findings

- The study found that using LUNA-qualifying products for the model high school parking application was not only an effective way to reduce light pollution, but also facilitated lower energy usage and greater cost savings compared to focusing on energy efficiency alone.
- For the model high school application, the study concluded that designing to use lower light levels had a bigger impact on reducing light pollution than did the optical distribution of fixtures, their BUG rating, and the use of shields. Using fixtures with low CCTs (i.e., less blue light) significantly reduced light pollution. See the DLC's Seven Strategies to Minimize Negative Impacts of Outdoor Light at Night resource for more information on how enabling controllability and reducing overlighting are the most effective strategies for reducing light pollution.
- The use of LUNA-qualifying products for the main street application also reduced light pollution, although energy consumption findings for the street scenarios varied depending on fixture type and specific product selection.
- In a retrofit scenario, where pole locations were already fixed, the study found that there may be tradeoffs between meeting illuminance, uniformity, and ordinance requirements.

Payback Period Findings

- The research team found that the ratio of realized energy savings to potential fixture costs clearly favored the use of LUNA products in many of the examined scenarios, but not all.
- Adding networked lighting controls (NLCs) altered the cost-effectiveness for both the model high school and main street projects. In all cases, using LUNA products along with an NLC system to dim LEDs to 20% of full power during the night (when the parking lot would be unoccupied and when traffic was lighter) provided additional energy savings.
- While adding NLCs was advantageous in terms of energy usage and light pollution reduction, it was not a cost-effective option due to the small-scale applications that were considered, and it increased the payback period of the lighting systems in general. From an economic standpoint, NLCs would receive a higher return on investment in larger installations.

Although energy savings and overall benefits varied somewhat from scenario to scenario, the findings indicate clear justification for utilities and other energy efficiency programs to incentivize LUNA-qualified products.

1. Introduction

Purpose

The purpose of this project was to evaluate the case for minimizing light pollution by exploring the energy use and cost impacts of outdoor lighting retrofit solutions that are both energy efficient and minimize light pollution compared to those that focus on energy efficiency alone. This project involved real-world scenarios to help municipal decisionmakers understand the energy implications of using fixtures qualified under DLC SSL V5.1 that are not eligible for LUNA compared to LUNA-eligible or LUNA-qualified products, and to help energy efficiency program administrators calculate the savings value attributed to LUNA products.

The base case condition was selected to be outdoor lighting fixtures with high intensity discharge (HID) lamps, such as metal halide (MH) and high pressure sodium (HPS). While outdoor lighting has mostly transitioned to LED technology, using HID as the base case allowed the researchers to simultaneously understand the benefits of LED fixtures on energy efficiency while also understanding the impact LED fixtures have on light pollution from a spectral perspective. Recent research has shown that light pollution has increased at rate of almost 10% per year in the same time period that LED outdoor lighting was becoming dominant (2011-2022). Most installed outdoor LED fixtures today have correlated color temperatures (CCTs) ranging from 3000K-5000K (with many early generation LED products in the 4000K-5000K range), compared to HPS fixtures with a CCT of 2000K and MH fixtures with CCTs typically ranging from 3000K-5000K.

Methodology

The research approach included conducting comparative application analyses for the outdoor end-use applications proposed by the DLC and shown in **Table 1**.

Table 1: End-use application scenarios proposed by the DLC.

		Base Case Condition (Ignores Light Pollution)	Retrofit Scenario 1 (Ignores Light Pollution)	Retrofit Scenario 2 (LUNA)
K-12 school building	Lighting Zone	LZ2 – Light commercial business/Mixed use residential		
	Source	4000K Metal Halide	4000K LED	3000K LED
	Parking lot	Area (e.g., Shoebox)	Area (U0)	LUNA Area (U1 max), house side shield used in fixtures on the perimeter
	Walkway	Pedestrian decorative	Decorative (U3/U4)	2.A. LUNA decorative (U2 max) 2.B. LUNA bollard (U1 max)
	Wallpacks	Non-cutoff	Semi-cutoff (U2 +)	LUNA wallpack (U1 max)
Town Main Street	Lighting Zone	LZ2 – Light commercial business/Mixed use residential		
	Source	2000K HPS	4000K LED	3000K LED
	Luminaire	Roadway	Decorative (e.g., Acorn) (U3 +)	LUNA Decorative (U2 max)

In all scenarios discussed below, AGi32 lighting application software was used to compare and calculate differences in photometric and energy performance among the lighting application scenarios. Also, in all cases, light pollution contributions were quantified using the performance method of the Joint IES/IDA Model Lighting Ordinance (MLO).

Criteria specific to each scenario were established to represent each hypothetical owner's project requirements in keeping with common practices. Owner project requirements included complying with all applicable Illuminating Engineering Society (IES) guidelines and recommended practices, energy codes, and light pollution requirements in MLO and local standards. IES recommendations were used for life cycle cost analysis calculations and sensitivity analyses on payback periods and return on investment (ROI) calculations were completed for various project configurations and electricity rates.

2. Lighting Application Site 1: Model High School (HS)

Site Selection

Site selection for the K-12 school was based on several factors, including selection of a site whose existing fixture types are covered in the LUNA Technical Requirements. These fixture types included pole-mounted area fixtures lighting a parking lot, pole-mounted pedestrian-scale fixtures illuminating walkways, and building-mounted fixtures (i.e., wallpacks). Parameters also included modeling energy and light pollution analyses for a location that represents an "average U.S. high school" in terms of population, and one located in a town with a comprehensive outdoor lighting ordinance using the latest energy code (i.e., ASHRAE 90.1-2019). It was also important to select a location served by DLC utility program members and representative of realistic application scenarios encountered by DLC stakeholders.

After exploring various sites across the U.S., it was determined that a high school site (HS) in northern Colorado met most of the above criteria and could be used as a model for this application area. The model site contains multiple parking lots with assorted sizes and shapes illuminated by pole-mounted area fixtures and has multiple pedestrian walkways of different lengths and widths illuminated by pole-mounted pedestrian fixtures and wallpacks. The population of Fort Collin's metropolitan statistical area (MSA) is 362,533, which is near the median MSA population across the U.S. (275,435 people). Fort Collins' lighting ordinance is exceptionally comprehensive[1], providing requirements for BUG ratings[2], limits on luminous flux output and horizontal illuminance at the property line, and a color temperature (CCT) requirement of 3000K or lower. Additionally, the DLC utility member Xcel Energy operates in Colorado, and Fort Collins has adopted the latest U.S. energy code (ASHRAE 90.1-2019). Based on Google Earth images and site visits, all parking lot and pedestrian scale fixtures were previously high intensity discharge (HID) sources but have been retrofitted with LEDs; the existing wallpacks are still HID fixtures.

[1] https://www.fcgov.com/developmentreview/files/final-code.pdf?1616795442
[2] https://www.ies.org/wp-content/uploads/2017/03/TM-15-11BUGRatingsAddendum.pdf?_ga=2.212985040.534774490.1687917739-1060764914.1686683638

Lighting Design

Base Case Condition

To simulate realistic lighting conditions, the lighting design for the model HS Base Case Condition was based on existing fixture locations and heights for pole-mounted and wallpack fixtures. A hypothetical run of bollards illuminating a walkway in the northeast part of the site leading to the large parking lot was added. The fixture selection followed the ANSI/IES RP-43-22[3] requirements for Lighting Zone 2 (LZ2) for the building entrance, drop-off, pick-up, and walking surfaces; the ANSI/IES RP-8-21[4] requirements for parking lots and drive lanes; and the Larimer County Urban Area Street Standards (2021)[5] for the local road within the site. These requirements are summarized in **Table 2.** The current Fort Collins Lighting Ordinance (FCLO) was not used for the Base Case Condition since it was not adopted until 2021. Instead, ASHRAE 90.1-2007 for LZ2 was followed and the overall lighting power density (LPD) allowance for the site was calculated in W/ft^2.

Table 2: Illuminance and uniformity requirements for the model high school.

	Application	Horizontal Illuminance at 0' AFG	Uniformity
RP-43-22 (LZ2)	Building Entrance, Drop-Off, Pick-Up	**Avg:** 1-2 fc	**Avg/Min:** 5:1
	Walking Surfaces	**Avg:** 1-2 fc	**Avg/Min:** 10:1
RP-8-21	Parking Lots & Drive Lanes	**Min:** 0.2 fc	**Max/Min:** 20:1
Larimer County Urban Area Street Standards (2021)	Local Road, Medium Pedestrian Activity	**Avg:** 0.9 fc	**Avg/Min:** 6:1

Most existing fixtures (except HID wallpacks) in the model HS have been upgraded to LED, so assumptions were made about common legacy fixtures, consistent with the design criteria of interest to the DLC (**Table 1**). An assumption of a consistent metal halide light source for the entire site and distributions and selected fixture wattages were made to meet the project illuminance and uniformity requirements summarized in **Table 2**.

The fixture schedule for the model HS Base Case Condition is summarized in **Table 3**.

[3] https://store.ies.org/product/rp-43-22-recommended-practice-lighting-exterior-applications
[4] https://store.ies.org/product/recommended-practice-lighting-roadway-and-parking-facilities
[5] https://www.larimer.gov/sites/default/files/uploads/2021/ch15_-_street_lighting_2.pdf

Table 3: Fixture schedule for Base Case Lighting Condition of the model high school.

Image	Type	Arrangement	Manufacturer	Catalog Number	Quantity	Distribution Type	Fixture Lumens	Fixture Watts	Mounting Height	BUG Rating
	A	Single	Holophane	SMST400MH00XXPM	18	III	29,770	442	27	B4-U0-G3
	B	Single	Holophane	SMST400MH00XXPM	4	III	29,770	442	41	B4-U0-G3
	B2 @180	Back-Back	Holophane	SMST400MH00XXPM	10	III	29,770	442	41	B4-U0-G3
	C	Single	Bega	7275MH	6	V	6,384	126	3	B2-U5-G3
	P	Single	Holophane	SMST70MH00XXPM	16	II	4,070	88	12	B1-U0-G1
	W1	Single	Holophane	W4150MH00UX	19	IV	8,641	183	25	B1-U4-G4
	W2	Single	Holophane	W435MH00UX	1	IV	1,417	44	11.5	B0-U3-G2

The control scenario for the model HS Base Case Condition followed ASHRAE 90.1-2007 requirements. This and all other control scenarios in this study made use of an astronomical timer and photocell to turn lights on and off. For this Base Case, lights turned on at dusk and off at dawn. No dimming was considered for this scenario, since HID light sources have dimming limitations.

Retrofit Scenario 1 (RS1)

The fixture selection for the model HS Retrofit Scenario 1 (RS1) was based on the same requirements as the Base Case Condition, except the LED fixtures had to be listed on the DLC's SSL QPL. The FCLO was not used for RS1 because the scenario's goal was to focus on energy efficiency alone and ignore light pollution considerations.

Fort Collins' current energy code, ASHRAE 90.1-2019 for LZ2, was followed for this scenario.

To keep manufacturers consistent among different scenarios as best as possible, Acuity pole-mounted fixtures were used as much as possible for RS1, since Acuity had many IES files available for the Base Case Condition. The wallpack manufacturer was selected to be consistent with the RS2 scenario, which used a Cree LUNA V1.0-qualified product. A RAB Lighting bollard product was selected based on performance criteria. Distribution and power consumption of the fixtures were selected to meet the same project requirements as the Base Case Condition to facilitate apples-to-apples energy efficiency comparisons among the scenarios, and fixtures with 4000K CCTs were selected. The fixture schedule for the model HS for RS1 is summarized in **Table 4.**

Table 4: Fixture schedule for Retrofit Scenario 1 (RS1) lighting condition of the model high school.

Image	Type	Arrangement	Manufacturer	Catalog Number	Quantity	Distribution Type	Fixture Lumens	Fixture Watts	Mounting Height	BUG Rating
	AR1	Single	Lithonia	RSX2 LED P6 40K R3	18	III	30,266	247	27	B3-U0-G4
	BR1	Single	Lithonia	RSX2 LED P6 40K R3	4	III	30,266	247	41	B3-U0-G4
	B2@ 180 R1	Back-Back	Lithonia	RSX2 LED P6 40K R3	10	III	30,266	247	41	B3-U0-G4
	CR1	Single	RAB	BLEDR24N	6	V	2,815	23	3	B2-U3-G2
	PR1	Single	Lithonia	DSX0 LED P1 40K 70CRI T2M	16	II	4,736	33	12	B1-U0-G2
	W1R1	Single	Cree	C-WP-C-TR-S10L-SCCT-UL-DB	19	IV	10,169	68	25	B2-U4-G4
	W2R1	Single	Cree	C-WP-C-TR-S6L-SCCT-UL-DB	1	IV	2,380	16	12.5	B1-U3-G2

The control scenario for HS RS1 followed ASHRAE 90.1-2019. Lights were scheduled using networked lighting controls to turn on at full power at dusk and dim to 50% of full power between midnight and dawn when no occupancy was detected for 15 minutes.

Retrofit Scenario 2 (RS2)

The fixture selection for the model HS with RS2 was based on the same requirements as the Base Case Condition and RS1, except the fixtures were chosen to meet LUNA Technical Requirements. Overlighting was minimized as much as practically possible while still meeting minimum IES illuminance criteria.

The FCLO was used for RS2 because the scenario's goal was to focus both on energy efficiency and light pollution considerations. The model high school is in a Lighting Context Area 1 location where the lighting ordinance required a glare (G) rating of G1 or lower. Due to the lower light output performance of LED fixtures with G1 ratings and the need to use existing pole locations, it was not possible to consistently comply with the G1 requirement in the FCLO and still meet the area light level requirements recommended by the IES or the Larimer County Urban Area Street Standards. To accommodate

RS2 Fixture Selection

It was impossible to meet the IES-recommended light levels or the Larimer County Urban Area Street Standards for RS2 with existing pole locations **and** comply with the G1 glare requirement of the FCLO due to the lower light output performance of LED fixtures with G1 ratings. Products with higher G ratings were used to accommodate this challenge, which resulted in a more direct energy efficiency comparison between RS1 and RS2.

this challenge, products with higher G ratings were allowed (which are associated with higher light output fixtures) in order to meet the IES and Larimer County illuminance recommendations. This also facilitated a more direct energy efficiency comparison between RS1 and RS2.

For this scenario, Fort Collins' current energy code, ASHRAE 90.1-2019 for Lighting Zone 2 (LZ2) was followed.

Again, for manufacturer and product consistency, Acuity pole-mounted fixtures meeting LUNA V1.0 requirements were used, and a Cree wallpack product listed on the LUNA QPL was selected for RS2. A Signify bollard product that would meet the LUNA V1.0 requirements was also selected. Distributions and wattages of the fixtures were selected to meet the same project requirements as the Base Case Condition and RS1, while meeting the FCLO requirements (except the G Rating). CCT of 3000K was selected to minimize light pollution. The fixture schedule for the HS RS2 is summarized in **Table 5**.

Table 5: Fixture schedule for Retrofit Scenario 2 (RS2) lighting condition of the model high school.

Image	Type	Arrangement	Manufacturer	Catalog Number	Quantity	Distribution Type	Fixture Lumens	Fixture Watts	Mounting Height	BUG Rating
	AR2	Single	Lithonia	RSX2 LED P6 30K R3	13	III	27,548	247	27	B3-U0-G4
	AR2@ 180	Back-Back	Lithonia	RSX2 LED P2 30K R3	2	III	15,657	114	41	B2-U0-G3
	AR2@ 180_B	Back-Back	Lithonia	RSX2 LED P2 30K R3S	1	III S	16,075	114	41	B2-U0-G2
	AR2_B	Single	Lithonia	RSX2 LED P2 30K R3	5	III	15,657	114	27	B2-U0-G3
	AR2_HS	Single	Lithonia	RSX2 LED P2 30K R2 HS	3	II HS	11,878	114	41	B1-U0-G2
	B2@ 180 R2_B	Back-Back	Lithonia	RSX2 LED P4 30K R3	7	III	22,755	190	41	B3-U0-G4
	BR2_B	Single	Lithonia	RSX2 LED P4 30K R3	1	III	22,755	190	41	B3-U0-G4
	CR2	Single	Signify	PBL-14L-450-WW-G2-5-UNV	6	V	2,195	23	3	B2-U0-G1
	PR2	Single	Lithonia	DSX0 LED P1 30K 70CRI T2M	16	II	4,544	33	12	B1-U0-G2
	W1R2	Single	Cree	XSPW-B-WM-4ME-8L-30K-UL	19	IV	8,475	77	25	B1-U0-G2
	W2R2	Single	Cree	XSPW-B-WM-4ME-2L-30K-UL	1	IV	2,490	20	12.5	B1-U0-G1

The control scenario for the model HS RS2 followed ASHRAE 90.1-2019 and LUNA requirements. Lights were scheduled to turn on at full power at dusk and dim to 20% of full power between midnight and dawn.

Light Pollution Calculations

The same parameters were used as the photometric calculations, but the light loss factor was changed to one to comply with requirements of the IDA/IES MLO. To quantify light pollution predictions for each scenario, the MLO tool within AGi32 was used. A report was generated for each scenario that summarized compliance with the MLO based on maximum allowed light levels on the vertical planes surrounding the site, total lumen allowance, and maximum offsite lumens.

Horizontal property line readings and BUG ratings were evaluated to determine compliance with the FCLO. Requirements in other parts of the local FCLO ordinance overlapped with the MLO requirements.

In addition, the scotopic relative sky glow (RSG)[6] was computed for select sources at the model HS. RSG describes sky glow associated with a light source's spectral power distribution relative to a defined reference spectrum. Standard HPS was used as the reference condition. Results are provided in **Table 6**. Overall, the chosen light sources had below average RSG compared to the range of possible RSG calculated by Esposito and Radetsky (2023).

[6] Pacific Northwest National Laboratory (PNNL). Sky glow comparison tool version 1.0. PNNL-SA-138348 [Internet]. [accessed 2022 Apr 25]. https://www.energy.gov/eere/ssl/potential-impacts-led-street-lighting-sky- glow.

Table 6: Scotopic relative sky glow (RSG) for select fixtures for the model high school.

Image	Fixture Description	RSG (relative to HPS)	Calculated CCT
	1. MH Example (from DOE Sky Glow Comparison Tool)	2.5	3925
	2. AR2_RSX2 LED P1 30K	2.1	3068
	3. CR1_BDLEDR24N	2.8	4087
	4. CR2_WW	2.3	2904
	5. PR1_DSX1 LED P4 40K 70CRI	2.7	4043
	6. PR2_DSX2 LED P8 30K 70CRI	2.1	3084
	7. W1R1_XSPW-30K	2.1	2966
	8. W1R2_WP52-50W-40K	3.1	4113
	9. W2R1_WP52-30W-40K	3.1	4071

Summary Results: Model High School

In general, all three scenarios met the average, minimum, and uniformity illuminance requirements in the parking lots and walkways based on the relevant standards, with a few exceptions. For the Base Case scenario, most parking lots exceeded the allowable maximum-to-minimum uniformity ratio. Due to the pole location limitations, a few points in the small parking lot were below the minimum illuminance requirements in all three scenarios. A few areas exceeded the maximum-to-minimum illuminance requirements in RS1, dropping to one area in RS2. In general, uniformity and minimums improved under RS1 and even more under RS2.

The power demand was reduced by 49.4% between the Base Case Condition and the RS1. It was further reduced by 20.86% between the RS1 and the RS2. See **Table 7**.

Table 7: Model high school lighting power densities (LPDs) for all scenarios

	Base Case	RS1	RS2
Area (ft²)	620,975	620,975	620,975
Total Watts (W)	24,409	12,348	9,806
LPD (W/ft²)	0.039	0.020	0.016

Light Pollution Reductions

Offsite lumens per the MLO decreased by 2.8% between the Base Case Condition and the RS1. They dropped by 33.1% between RS1 and RS2. This result was expected because the significant reduction correlates with the choice of fixtures and minimized overlighting. See **Figure 1** for a comparison. All vertical boundary planes in the RS2 layout met the MLO requirements. There were some points that exceeded the maximum allowable illuminance in the MLO requirments for the top plane, but there were fewer of these points compared to the other scenarios.

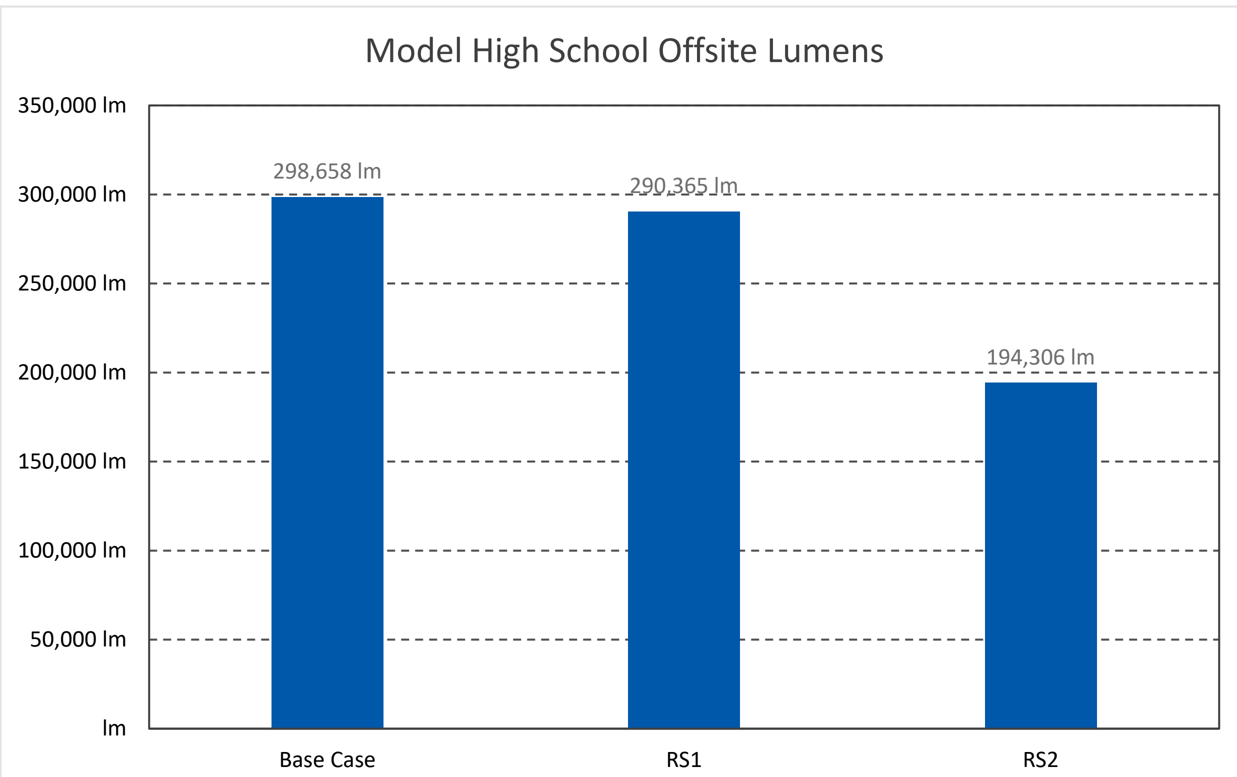

Figure 1: Model high school offsite lumen comparison.

The values above are photometric, meaning they do not include spectral weighting factors, which are captured with the RSG metrics shown in **Table 6.** When the offsite lumens are weighted by RSG, as shown in **Table 8**, the 4000K metal halide Base Case fixtures (with an RSG of 2.5) have much higher weighted offsite lumens. With 4000K fixtures in RS1 (with an average RSG of 2.8), the weighted sky glow increased to 109%, even though the total number of (photometric) lumens leaving the site decreased by

2.8%. Sky glow decreased with 3000K fixtures in RS2 compared to metal halide, due to the product of lower RSG (2.2) and lower total (photometric) lumens leaving the site.

Table 8: Relative light pollution reduction for the model high school when weighted by relative sky glow (RSG).

Scenario	Average RSG (fixture weighting)	Total offsite lumens (photometric)	Total offsite lumens (weighted by RSG)	Relative offsite light pollution
Model HS Base Case	2.5	298,658	746,645	1.00
Model HS RS1	2.8	290,365	813,022	1.09
Model HS RS2	2.2	194,306	427,473	0.57

3. Lighting Application Site 1: College Ave.

Site Selection

The site selection for the town main street was based on similar parameters as the high school, but it primarily included pole-mounted roadway, area, and decorative fixtures. Fort Collins' main roadway, College Ave., was selected for analysis and had several roadway fixture types present in various stretches: roadway (e.g., cobrahead) (Laporte Ave. to Maple St.), and area (e.g., shoebox) and decorative pedestrian fixtures (Mountain Ave. to Laporte Ave.) (see **Figure 2).**

Figure 2: College Ave. selected stretches.

Lighting Design

The two stretches of College Ave. were divided into three design scenarios:

1. The “**Roadway**” scenario for the top stretch of College Ave. between Laporte Ave. and Maple St., using existing roadway lighting fixture locations and the measured mounting height of 33 ft (see **Figure 3**);
2. The “**Area Lighting**” scenario for the bottom stretch of College Ave. between Mountain Ave. and Laporte Ave., using existing area lighting locations and the measured mounting height of 52.5 ft (ignoring existing decorative pedestrian fixtures as they were few and far between and not intended to illuminate the road) (see **Figure 4**);
3. The “**Decorative**” scenario for the bottom stretch of College Ave., which was not based on existing fixture locations and used a hypothetical layout and a mounting height of 18 ft (see **Figure 5**).

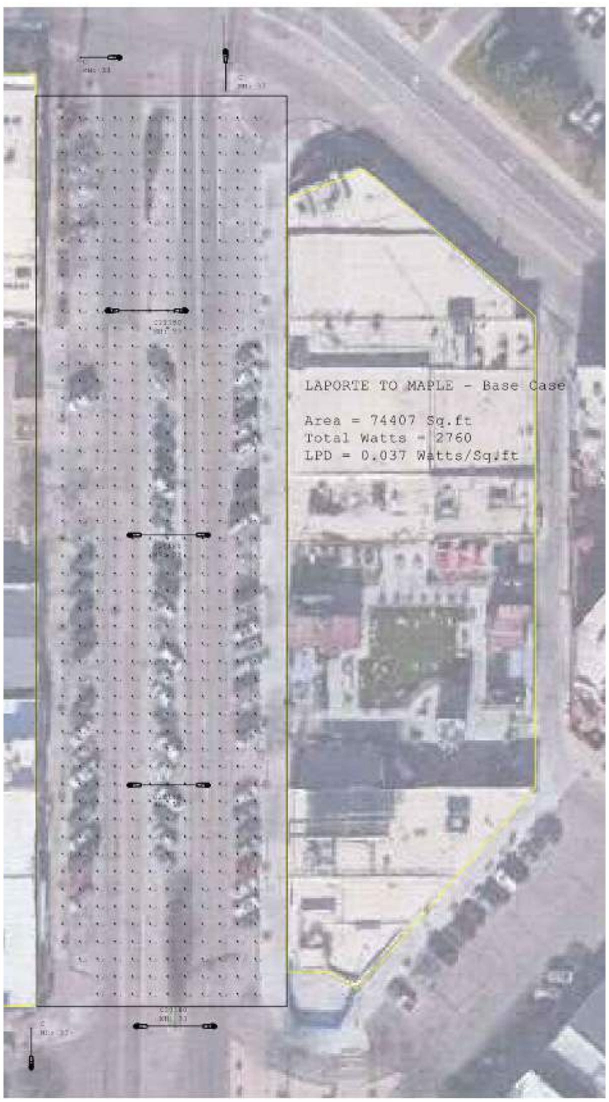

Figure 3: College Ave. Roadway layout.

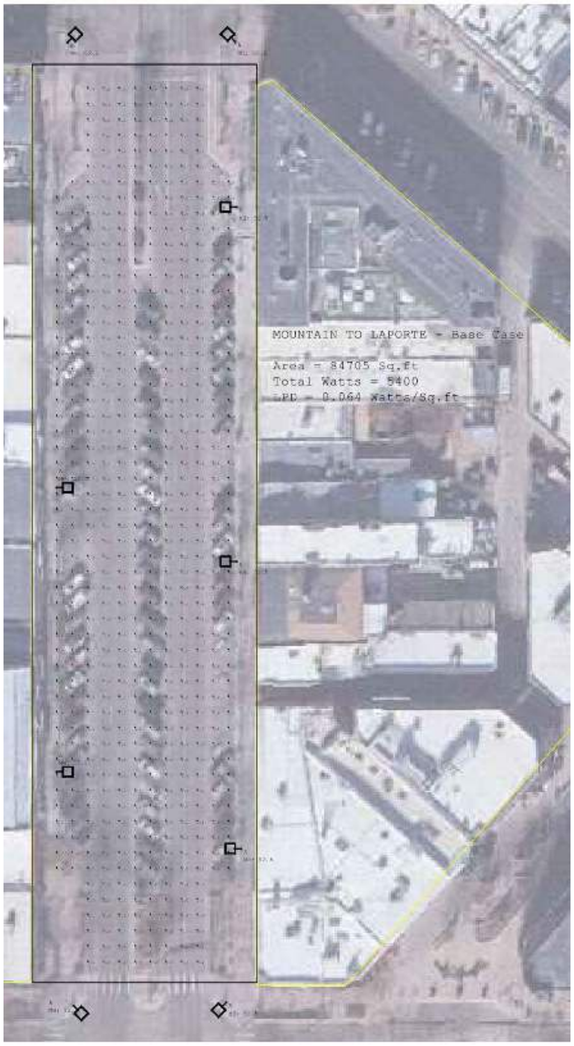

Figure 4: College Ave. Area layout.

Figure 5: College Ave. Decorative (e.g., Acorn) layout.

Base Case Condition

The fixture selection for the Base Case Condition followed the Larimer County Urban Area Street Standards (2007)[7] for the Roadway and Area Lighting Scenarios. The standard called for 400 W HPS Type 3 cobrahead-style roadway fixtures and for 1000 W metal halide shoebox-style area lighting fixtures for the respective stretches of College Ave. Type 3 distributions were selected for the area lighting fixtures, as well. The Larimer County standard also included light level requirements based on the Arterial Street classification and Commercial Area classification from the City of Fort Collins website[8]. Fixture selection for the Decorative Scenario was based on available IES files with metal halide lamps and on the light output and distribution needed to achieve required light levels. The Roadway and Area Lighting Scenarios included additional fixtures located at intersections, as their contributions helped achieve or approach necessary light levels, but were not included in the light pollution or energy calculations.

[7] https://www.larimer.org/sites/default/files/ch07_redlilnes.pdf
[8] https://gisweb.fcgov.com/HTML5Viewer/Index.html?Viewer=FCMaps&layerTheme=Master%20Street%20Plan

The College Ave. scenarios, which represent city street lighting, are not powered by the building electrical system and therefore are unregulated by building energy codes. Hence, no energy code comparisons or analyses were conducted.

The fixture schedule for the College Ave. Base Case Condition is summarized in **Table 9.**

Table 9: College Ave. Base Case Condition fixture schedule.

Image	Type	Arrangement	Manufacturer	Catalog Number	Quantity	Distribution Type	Fixture Lumens	Fixture Watts	Mounting Height	BUG Rating
Roadway										
	C	Single	Holophane	125 40S R3 DG	3	III	37,495	460	33	B4-U4-G4
	C2 @180	Back-Back	Holophane	125 40S R3 DG	4	III	37,495	460	33	B4-U4-G4
Area										
	A	Single	Spaulding Lighting	CE2-H1K-H3-F	9	III	53,661	1080	52.5	B5-U0-G5
Decorative										
	B2 @180 TWIN	Twin	Holophane	WA250MH00X4X4	10	IV	23,432	283	18	B4-U5-G5

The control scenario for the College Ave. Base Case Condition followed similar requirements to the model HS, with lights turning on at dusk and off at dawn. No dimming was assumed for this Base Case scenario, since HID lamps have limited dimming capabilities.

Retrofit Scenario 1 (RS1)

The fixture selection for the College Ave. Retrofit Scenario 1 (RS1) was based on the same illuminance requirements as the Base Case Condition, except the fixtures had to be listed on the DLC's SSL QPL. Light pollution mitigation was not prioritized in considerations for this scenario.

To keep manufacturers consistent among different scenarios as much as possible, Acuity fixtures were specified for the Base Case and RS1, since Acuity had many IES files available for the Base Case Condition. Distributions and light output of the fixtures were selected to meet the same illuminance requirements as the Base Case Condition so that the energy efficiency comparisons between the scenarios could be made fairly. Type 5 distributions were used for the decorative-style fixtures, as that was the only way to achieve the desired light levels in the middle of the street and meet the project requirements. A CCT of 4000K was used for this scenario. The fixture schedule for the College Ave. RS1 is summarized in **Table 10.**

Table 10: College Ave. Retrofit Scenario 1 (RS1) fixture schedule.

Image	Type	Arrangement	Manufacturer	Catalog Number	Quantity	Distribution Type	Fixture Lumens	Fixture Watts	Mounting Height	BUG Rating
Roadway										
	CR1	Single	Lithonia	ATBL G XXXXX R3	3	III	29,405	279	33	B3-U0-G5
	C2 @180 R1	Back-Back	Lithonia	ATBL G XXXXX R3	4	III	29,405	279	33	B3-U0-G5
Area										
	AR1	Single	Lithonia	RSX4 LED P2 40K R3	9	III	45,181	320	52.5	B4-U0-G5
Decorative										
	B2 @180 R1 TWIN	Twin	Holophane	AWDE3 P70 40K XXXX AL5	10	V	20,079	156	18	B5-U5-G5

The control scenario for the College Ave. RS1 scenario followed requirements similar to the model HS, with lights turning on at dusk and using scheduled dimming to 50% of full power between 3:00am and dawn when no occupancy was detected for 15 minutes. The dimming time was scheduled back to 3:00am due to considerable late-night pedestrian activity from bars and clubs in the area.

Retrofit Scenario 2 (RS2)

The fixture selection for the College Ave. Retrofit Scenario 2 (RS2) was based on the same requirements as the Base Case Condition and RS1, except the fixtures had to be DLC SSL QPL-listed and meet the LUNA V1.0 Technical Requirements.

Manufacturer types were more varied for the RS2 scenario due to performance considerations. The SSL QPL did not include a decorative replacement option with a U0 rating that would also meet the local light level requirements, so a slightly different style of decorative fixture was selected from Signify. Distributions and light outputs of the fixtures were selected to meet the same project requirements as the Base Case Condition and RS1, while also minimizing light pollution. The roadway and area light fixtures already had a U0 rating, so the main change in RS2 was decreasing the CCT from 4000K to 3000K. That necessitated using a different manufacturer for the roadway lighting fixtures (Cree) and increasing the wattage of the area fixtures, since the light output of those was lower, at 3000K. The fixture schedule for the College Ave. RS2 is summarized in **Table 11.**

Table 11: College Ave. Retrofit Scenario 2 (RS2) fixture schedule.

Image	Type	Arrangement	Manufacturer	Catalog Number	Quantity	Distribution Type	Fixture Lumens	Fixture Watts	Mounting Height	BUG Rating
Roadway										
	CR2	Single	Cree	RSWX-B-HT-3ME-32L-30K7-Ux-xx-N	3	III	29,000	248	33	B3-U0-G5
	C2 @180 R2	Back-Back	Cree	RSWX-B-HT-3ME-32L-30K7-Ux-xx-N	4	III	29,000	248	33	B3-U0-G5
Area										
	AR2	Single	Lithonia	RSX4 LED P3 30K R3	9	III	45,865	369	52.5	B4-U0-G5
Decorative										
	B2 @180 R2 TWIN	Twin	Signify	RNx0-145W64LED3K-G3-LE5F	10	V	16,599	140	18	B4-U0-G2

The control scenario for the College Ave. RS2 followed requirements similar to the model HS, with lights turning on at dusk and dimming to 20% of full power (following LUNA requirements) between 3:00am and dawn when no occupancy was detected for 15 minutes.

Light Pollution Performance

To quantify light pollution performance for each scenario, the IDA/IES MLO tool was used within AGi32 software.

In addition to the MLO light pollution calculations, RSG[9] for select sources was computed at College Ave., using standard HPS as the reference condition. Results are provided in **Table 12**.

Overall, the chosen light sources had below-average RSG compared to the range of possible RSG values (demonstrated by Esposito and Radetsky [2023][10]) for spectra at the same nominal CCT.

[9] Pacific Northwest National Laboratory (PNNL). Sky glow comparison tool version 1.0. PNNL-SA-138348 [Internet]. [accessed 2022 Apr 25]. https://www.energy.gov/eere/ssl/potential-impacts-led-street-lighting-sky- glow.
[10] https://doi.org/10.1080/15502724.2022.2121285

Table 12: Scotopic relative sky glow (RSG) and CCT values for select fixtures for College Ave.

Image	Fixture Description	RSG (relative to HPS)	Calculated CCT
	1. HPS Roadway Example	1.0	2040
	2. MH Area Lighting Example (from DOE Sky Glow Comparison Tool)	2.5	3925
	3. AR1 DSX1 LED P4 40K 70CRI	2.7	4043
	4. AR2 RSX1 LED P3 30K	2.2	3136
	5. BR1 WAE3 P50 40K	2.7	3902
	6. BR2 L2207276	2.2	3108
	7. CR1 ATBL A R4 4K	2.7	4087
	8. CR2 RSWX-B-HT-2ME-32L-30K7	2.3	3081

Summary Results: College Ave.

The average illuminance requirements in the Larimer County Urban Street Lighting Standards (2021) were met with all fixture types in all scenarios. Due to existing pole locations, however, the average to minimum uniformity requirements were exceeded for the roadway and area lighting layouts. The hypothetical decorative (e.g., acorn) layout, which did not use existing pole locations, was able to meet the uniformity requirements.

Lighting Power Comparisons

- Using roadway lighting fixtures, power demand decreased by 39.3% between the Base Case Condition and RS1, and by an additional 11.1% between RS1 and RS2.
- Using area lighting fixtures, power demand decreased by 70.3% between the Base Case Condition and the RS1 and increased by 15.2% between the RS1 and RS2. The increase in power demand in RS2 was due to needing to use higher wattage 3000K fixtures.
- Using decorative lighting fixtures, power demand decreased by 44.9% between the Base Case Condition and the RS1 and decreased an additional by 10.3% between RS1 and the RS2.

Table 13 shows how power demand and lighting power density mostly decreased between retrofit scenarios for different fixture types.

Table 13: College Ave. lighting power densities (LPDs) for all scenarios.

	Base Case	RS1	RS2
Roadway LPDs			
Area (ft^2)	74,407	74,407	74,407
Total Watts (W)	2,760	1,674	1,488
LPD (W/ft^2)	0.037	0.022	0.020
Area LPDs			
Area (ft^2)	84,705	84,705	84,705
Total Watts (W)	5,400	1,602	1,845
LPD (W/ft^2)	0.064	0.019	0.022
Decorative LPDs			
Area (ft^2)	84,705	84,705	84,705
Total Watts (W)	5,660	3,120	2,800
LPD (W/ft^2)	0.067	0.037	0.033

Light Pollution Comparisons

With roadway lighting fixtures, the top plane lumens decreased by 30.8% between the Base Case Condition and RS1, and decreased by an additional 0.2% between RS1 and RS2 (due to needing a higher lumen fixture to meet the light level requirements when the CCT was changed from 4000K to 3000K).

With area lighting fixtures, the top plane lumens decreased by 9.2% between the Base Case Condition and RS1, and increased by 1.5% between the RS1 and RS2 (due to needing a higher lumen fixture to meet the light levels requirements when the CCT was changed from 4000K to 3000K).

With decorative lighting fixtures, the top plane lumens decreased by 44.7% between the Base Case Condition and RS1, and decreased by an additional 39.2% between RS1 and RS2. This reduction is mostly due to the U0 rating for the selected LUNA-compliant decorative lighting fixtures.

See **Table 14** for a comparison of maximum illuminances and lumens on the top plane of the MLO boundary between scenarios and fixture types.

Table 14: **College Ave. light pollution performance.**

	Base Case	RS1	RS2
Roadway Light Pollution			
Top Plane Max Fc	0.8	0.5	0.5
Top Plane Lumens (TPL)	32,513	22,500	22,543
Area Light Pollution			
Top Plane Max Fc	0.4	0.4	0.4
Top Plane Lumens (TPL)	24,919	22,630	22,972
Decorative Light Pollution			
Top Plane Max Fc	2.1	1.2	0.6
Top Plane Lumens (TPL)	114,476	63,251	38,441

As previously noted, these values are photometric, and they do not include RSG weighting shown in **Table 12**. When the top plane lumens are weighted by RSG, as shown in **Table 15**, 4000K roadway lighting fixtures in RS1 (with an RSG of 2.7 for the selected luminaire) increased sky glow relative to HPS, even though the total number of (photometric) lumens leaving the site was decreased by 30.8%. Sky glow also increased with 3000K fixtures in RS2 compared to HPS, even though the total number of (photometric) lumens leaving the site was decreased by 31%. This impact is also seen in the real world.[11]

Compared to the Metal Halide Base Case for area lighting and decorative lighting (with an RSG of 2.5), 4000K area lighting fixtures and decorative lighting fixures selected in RS1 were able to reduce sky glow by 2% and 40%, respectively – the product of lower photometric lumens leaving the site but slightly higher RSGs. When 3000K area lighting fixtures and decorative lighting fixures were selected in RS2, sky glow reduced by 19% and 70% respectively, due to better optics and lower RSGs.

Table 15: Impact of relative sky glow (RSG) weighting factors with MLO calculations for College Ave. fixtures.

	Base Case	RS1	RS2
Top plane lumens – photometric (MLO)			
Roadway lighting fixtures	32513	22500	22543
Area lighting fixtures	24919	22630	22972
Decorative lighting fixures	114476	63251	38441
RSG			
Roadway lighting fixtures	1	2.7	2.3
Area lighting fixtures	2.5	2.7	2.2
Decorative lighting fixures	2.5	2.7	2.2
Weighted sky glow leaving site (including RSG)			
Roadway lighting fixtures	32513	60750	51849
Area lighting fixtures	62298	61101	50538
Decorative lighting fixures	286190	170778	84570
Relative light pollution reduction including RSG			
Roadway lighting fixtures	1.00	1.87	1.59
Area lighting fixtures	1.00	0.98	0.81
Decorative lighting fixures	1.00	0.60	0.30

4. Cost Analysis

To determine payback periods and return on investment (ROI), lifecycle cost analyses were conducted for each design scenario (RS1 and RS2 for the model HS, and RS1 and RS2 for College Ave. with three fixture types).

The following process was used to calculate the payback period and ROI:

1. Determined the capital cost of the designed lighting system for each scenario;

[11] https://doi.org/10.1016/j.jenvman.2021.112776

2. Determined applicable utility rebates**;**
3. Determined the annual operating cost for each scenario (maintenance and energy), and used this information to determine the annual operating cost savings of each retrofit scenario by comparing them to the annual operating cost of the Base Case scenario;
4. Determined the payback period by taking the capital cost less the amount of the utility rebates, divided by the annual operating cost savings (relative to the Base Case scenario) using the formula below:

$$\boldsymbol{Payback\ Period\ (years)} = \frac{\boldsymbol{Capital\ Cost - Utility\ Rebate}}{\boldsymbol{Annual\ Operating\ Cost\ Savings}}$$

5. Calculated the simple annual ROI using the formula below:

$$\boldsymbol{Return\ on\ Investment} = \frac{\boldsymbol{Annual\ Operating\ Cost\ Savings}}{\boldsymbol{Capital\ Cost - Utility\ Rebate}}\ \boldsymbol{x\ 100\%}$$

Step 1: Capital Cost

The capital cost of each lighting system was calculated as the sum of the upfront material cost of the fixtures and control system plus installation costs.

$$\boldsymbol{Capital\ Cost = Material\ Cost + Installation\ Cost}$$

To calculate *material capital cost* for each scenario, distributed net (DN) pricing was requested from local lighting sales agents whose line cards included the manufacturers of the fixtures and control systems in our application scenarios. To estimate realistic capital costs, a 15% markup was applied for the electrical distributor, a 20% markup for the electrical contractor, and a 7.55% local sales tax was applied.

Since most of the specified fixtures were from Acuity, Acuity's nLight Air control system (which is DLC-listed) was used for all scenarios. The control system costs included the cost of sensors, wall switches, repeaters, relays (for the model HS only), the "brain" of the control system, and commissioning.

To determine the realistic *capital installation (labor) cost* of the fixtures and the control system, a local lighting and electrical contractor was interviewed.

The capital costs for each scenario are summarized in **Table 16** and **Figure 6.** Overall, the model HS application used the most fixtures and therefore had the largest upfront capital cost. For the College Ave. scenarios, the decorative retrofit had a much higher capital cost due to two factors: the decorative fixtures had a higher material cost relative to the roadway or area lighting, and more fixtures were needed to achieve the same photometric performance.

Table 16: Material and installation cost estimates for Retrofit Scenario 1 and 2 for each lighting application scenario.

Site	RS1			RS2		
	Material	Installation	Total	Material	Installation	Total
Model High School	$89,747	$11,113	$100,860	$91,983	$11,113	$103,096
College Ave. (Roadway)	$12,453	$1,150	$13,603	$15,294	$1,150	$16,444
College Ave. (Area)	$14,610	$1,758	$16,368	$14,610	$1,758	$16,368
College Ave. (Decorative)	$32,750	$2,760	$35,510	$46,390	$2,760	$49,150

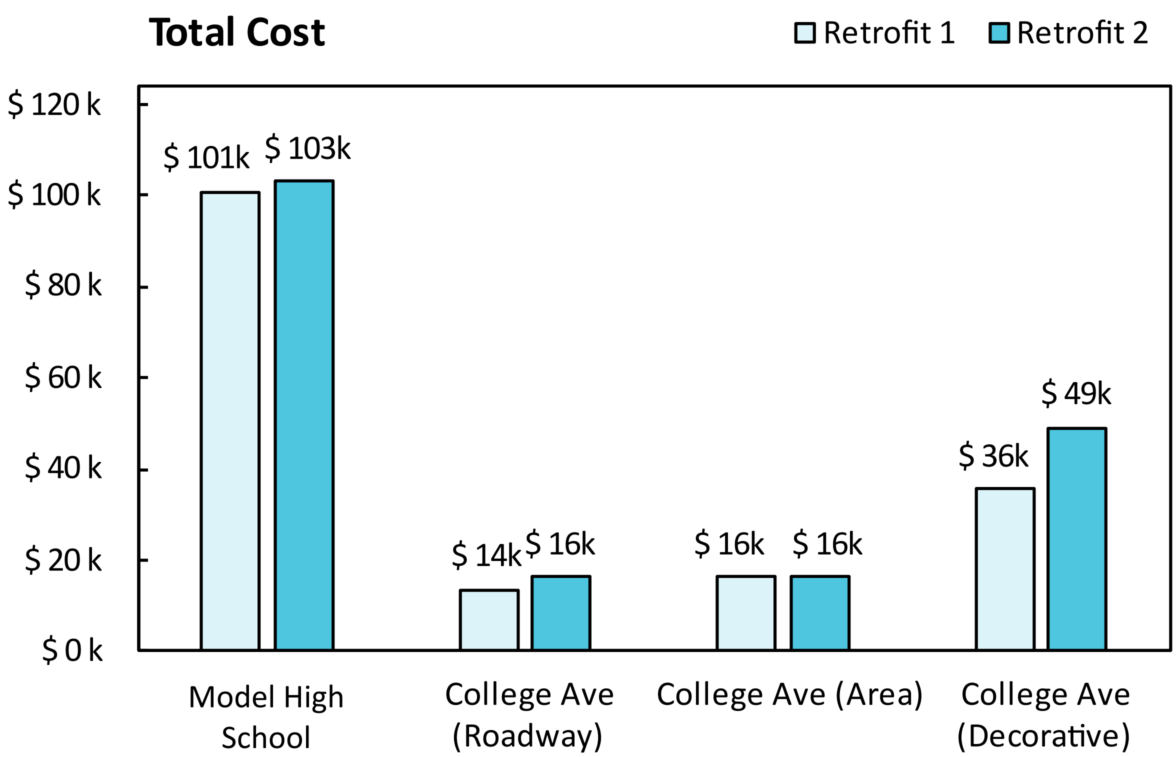

Figure 6: The total capital cost for both Retrofit Scenario 1 and 2 for each lighting application scenario.

Step 2: Utility Rebates

Two rebates available in Colorado were used in the lighting application scenarios.

Xcel Energy,[12] a utility operating in various localities in Colorado, offers a prescriptive rebate program, providing a set rebate amount per fixture depending on fixture type and power demand (in watts); DLC-listed fixtures are eligible for additional rebates. The values of the rebates are summarized in **Table 17**. In addition, Xcel Energy offers a control system rebate of $0.40 per watt of total controlled load when controlled by a networked control system.

[12] https://www.xcelenergy.com/programs_and_rebates

Table 17: Rebate amounts provided by Xcel Energy's prescriptive rebate program (as of June 2023).

	Per Fixture (Non-DLC)	Per Fixture (DLC)
Area lighting fixtures/Decorative fixtures		
45W-65W	$26.25	$35.00
66W-89W	$26.25	$35.00
90W-119W	$30.00	$40.00
120W-140W	$37.50	$50.00
141W-199W	$45.00	$60.00
200W-550W	$67.50	$90.00
Roadway fixtures		
55W-79W	$18.75	$25.00
80W-109W	$18.75	$25.00
110W-139W	$30.00	$40.00
140W-209W	$37.50	$50.00
Wallpacks		
10W-25W	$11.25	$15.00
26W-60W	$22.50	$30.00
61W-150W	$37.50	$50.00

The Fort Collins Utility rebate program[13], a custom/dynamic program that provides a rebate of $1.25 per watt of the total reduced load for fixtures and $0.50 per watt of the total controlled load for a DLC-listed NLC system was also used in ROI calculations.

The calculated rebates from both providers for RS1 and RS2 for each lighting application scenario are summarized in **Table 18** and **Figure 7**.

Table 18: Calculated rebates (including fixtures and controls) from two providers for Retrofit Scenario 1 and 2 for each lighting application scenario.

	Xcel Rebate			Fort Collins Utility Rebate		
Scenario	**Fixtures**	**Controls**	**Total**	**Fixtures**	**Controls**	**Total**
Model high school: RS1 (50% dim)	$5,305	$4,939	$10,244	$15,076	$6,174	$21,250
Model high school: RS2 (80% dim)	$4,155	$3,922	$8,077	$18,254	$4,903	$23,157
College Ave: RS1 (Roadway|50% dim)	$300	$670	$970	$1,358	$837	$2,195
College Ave: RS2 (Roadway|80% dim)	$300	$595	$895	$1,590	$744	$2,334
College Ave: RS1 (Area|50% dim)	$250	$640	$890	$4,750	$800	$5,550
College Ave: RS2 (Area|80% dim)	$250	$738	$988	$4,444	$923	$5,366
College Ave: RS1 (Decorative|50% dim)	$1,000	$1,248	$2,248	$3,175	$1,560	$4,735
College Ave: RS2 (Decorative|80% dim)	$1,000	$1,120	$2,120	$3,575	$1,400	$4,975

[13] https://www.fcgov.com/utilities/business/improve-efficiency

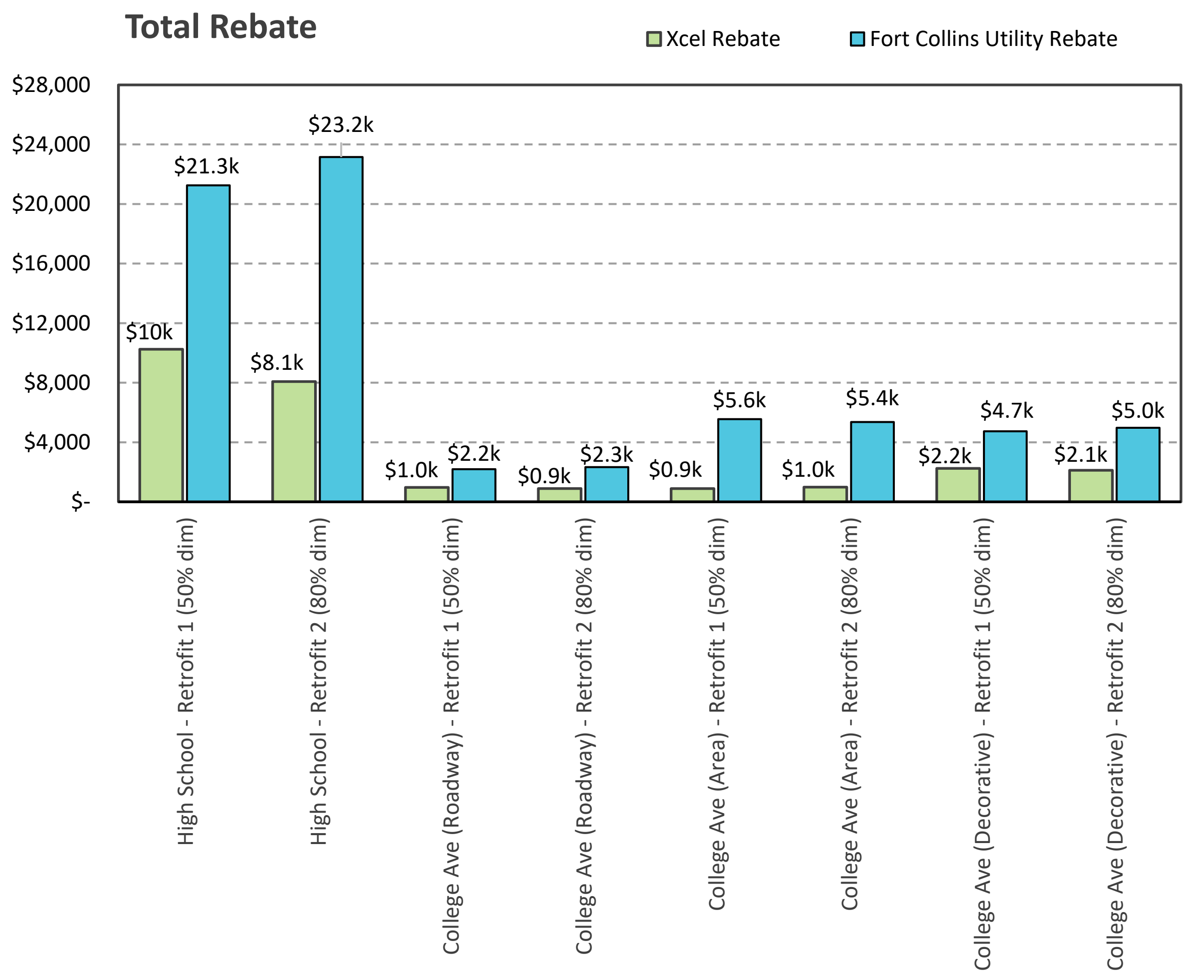

Figure 7: Total calculated rebate from two providers for Retrofit Scenario 1 and 2 for each lighting application scenario.

Step 3: Operating Cost

The annual operating cost was calculated as the sum of the annual energy cost and annual maintenance cost.

Annual Energy Cost

The annual energy cost was computed as the product of the total power demand (kW), total adjusted operating hours (h), and cost of electricity ($/kWh).

The total power consumption of each lighting application scenario was calculated by multiplying the power consumption (in watts) of each fixture type by the total quantity of fixtures of that type in the lighting application.

Fixtures in all scenarios were specified to be turned on at dusk and off at dawn, and then dimmed per the application scenario given in **Table 19** and **Figure 8**. The dusk and dawn times for Fort Collins each day of the year were determined using *Sunrise Sunset Calculator* from SunEarthTools[14], and exported to Microsoft Excel. The total possible operating hours were computed to be 4,305 hours.

Table 19: Scheduled dimming strategies for the various lighting application scenarios.

	Model HS			College Ave.		
	Base	R1	R2	Base	R1	R2
Dusk - Midnight	100%	100%	100%	100%	100%	100%
Midnight - 3 am	100%	50%	20%	100%	100%	100%
3 am - Dawn	100%	50%	20%	100%	50%	20%

Table note: The provided values represent the best-case energy savings scenario where the fixtures dim at their scheduled times and are never interrupted (i.e., they never detect activity and increase light levels to full light output).

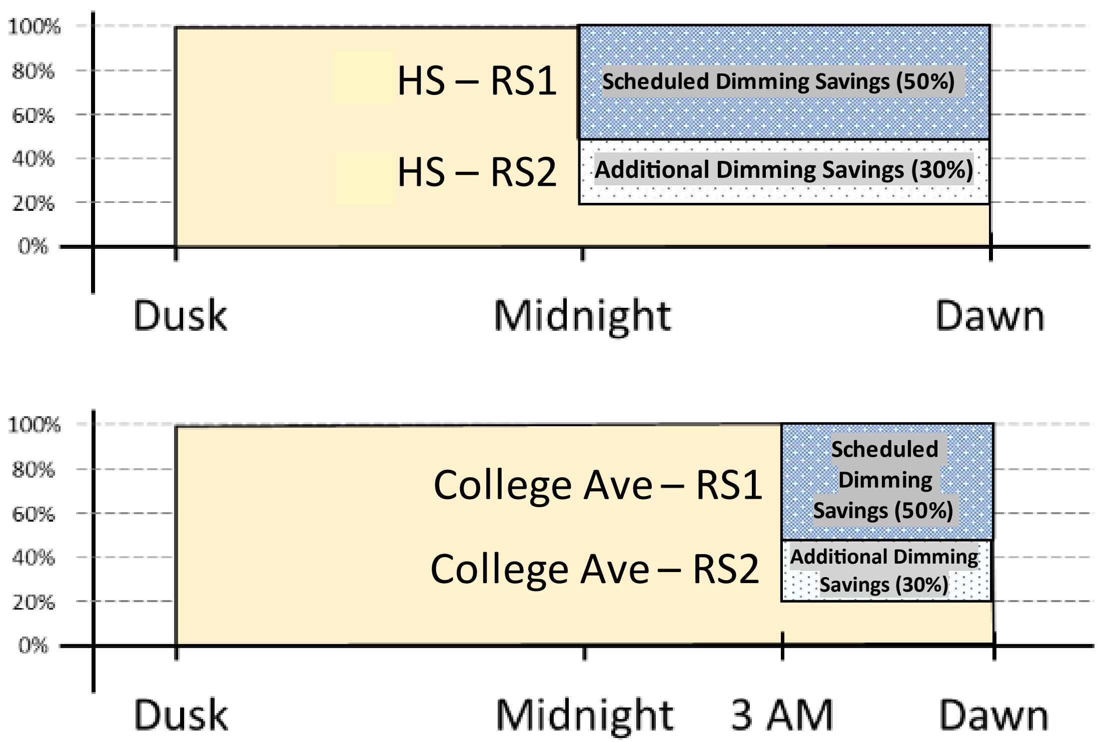

Figure 8: Top: A visual of the scheduled dimming periods in RS1 and RS2 at the model high school. Bottom: A visual of the scheduled dimming periods in RS1 and RS2 at College Ave.

Based on Fort Collins Utility electricity rates, the cost of electricity in summer (June-September) is $0.1071/kWh and in winter (January-May and October-December) is $0.1208/kWh. To accurately

[14] https://www.sunearthtools.com/solar/sunrise-sunset-calendar.php

calculate the total energy cost, the operating hours were sub-divided by these definitions of summer and winter.

Once the annual energy cost was determined, annual energy cost savings relative to the Base Case were computed by subtracting the energy cost of the retrofit from the energy cost of the Base Case. **Figure 9** shows the annual energy cost savings relative to the Base Case.

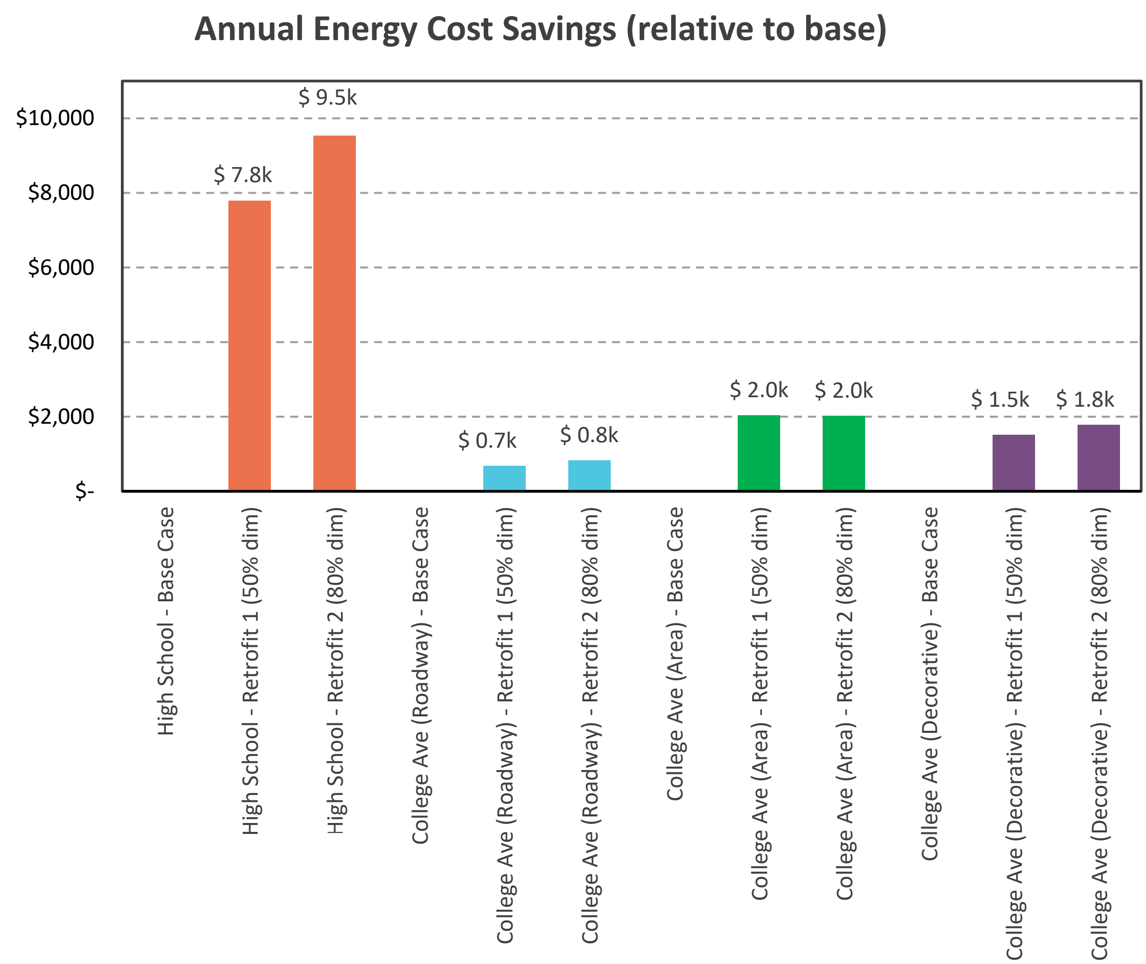

Figure 1: Annual energy cost savings relative to the Base Case scenario.

Annual Maintenance Cost

The annual maintenance cost was computed as the sum of the material and labor costs of lamp/fixture replacements and ballast/driver replacements, and the labor costs of fixture cleaning.

Base Case scenario:

All Base Case scenarios used either HPS or MH fixtures. As such, the annual maintenance cost was computed as the sum of the material and labor costs to replace lamps and ballasts. To provide realistic estimates, the fixtures were assumed to never be cleaned, as was confirmed by a local lighting and electrical contractor.

For simplicity, lamp replacements were calculated to occur at the end of their rated life. Based on a GE Lighting lamp catalog estimate, the study assumed 10,000 hours, 9,000 hours, and 24,000 hours, respectively, for the metal halide lamps in the model HS scenario and College Ave. Decorative scenarios, the metal halide lamps in the College Ave. Area Lighting scenario, and the HPS lamps in the College Ave. Roadway scenario.[15]

For simplicity, for all Base Case scenarios, ballast replacements were calculated to occur at the end of their rated life – 50,000 hours.[16] The maintenance cost estimates for the Base Case are shown in **Figure 10**.

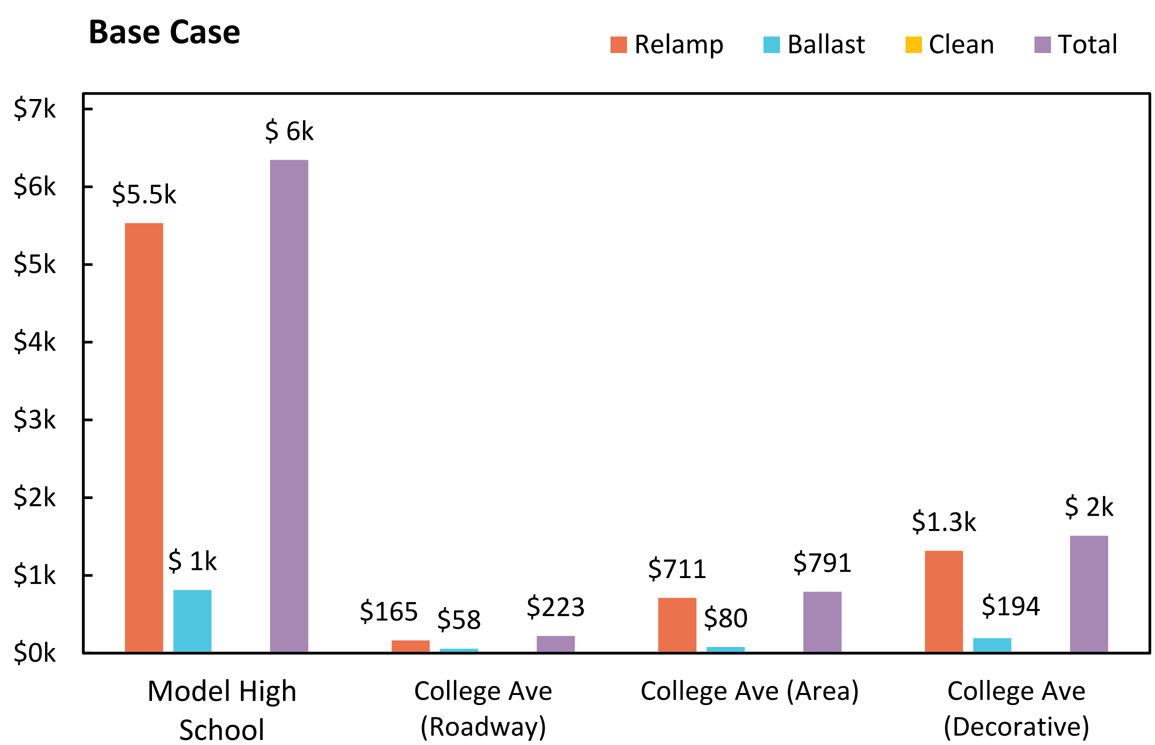

Figure 2: Maintenance cost estimates for the Base Case scenarios.

Retrofit scenarios:

All retrofit scenarios use DLC-qualified LED fixtures. As such, the annual maintenance cost was calculated as the sum of the material and labor costs to replace fixture failures and to replace drivers. Again, fixtures were assumed to never be cleaned.

Based on research of relevant literature, LED fixtures were determined to fail at a very low rate. Since some fixture failures seemed inevitable, 1% were assumed to fail over the lifetime of the LED lighting system. Similarly, review of the literature indicated an LED driver failure rate of one in 10 failures at the

[15] https://online.ogs.ny.gov/purchase/spg/pdfdocs/0540023083spec_8a-3,4,8,9GE.pdf

[16] https://www.federalregister.gov/documents/2022/10/06/2022-21696/energy-conservation-program-energy-conservation-standards-for-metal-halide-lamp-fixtures

typical rated life of a driver (50,000 hours), and this rate was used to compute the frequency of ballast replacement.

The annual maintenance costs for RS1 and 2 are summarized in **Figure 11**. With these assumptions, the annual maintenance cost of the LED systems was minimal.

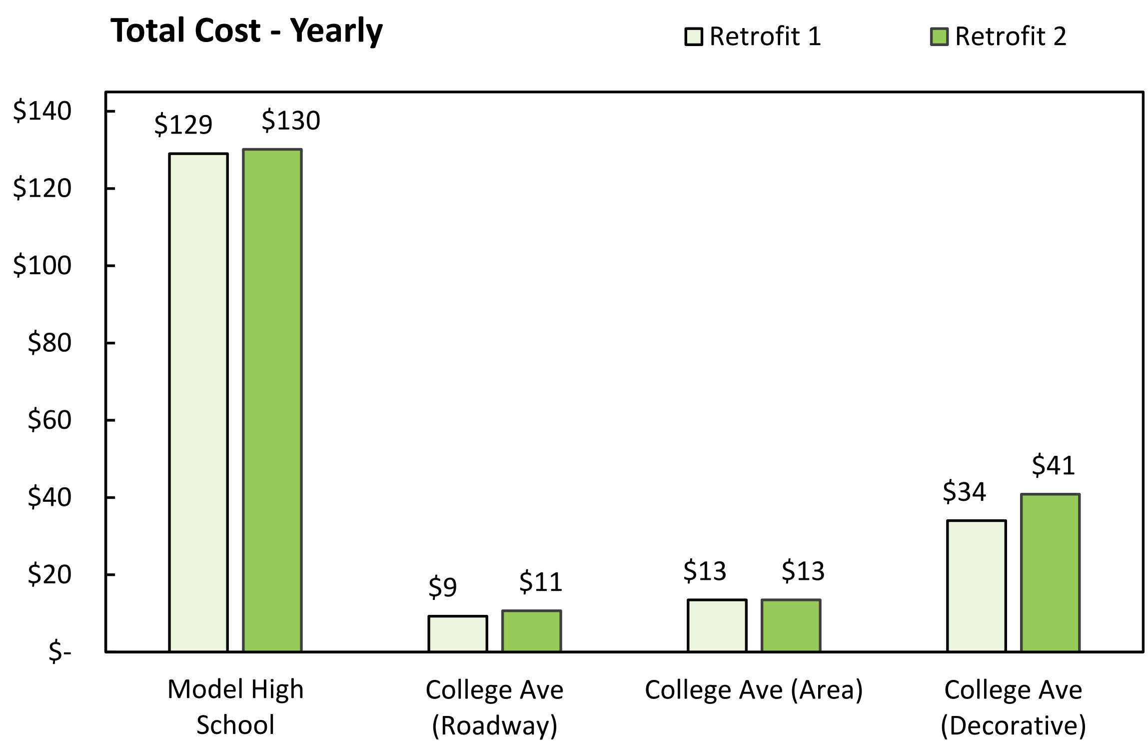

Figure 31: The annual maintenance cost for the LED lighting systems in Retrofit Scenario 1 and 2. The estimated maintenance costs were very low.

Simple payback period/ROI:

The payback period was calculated as the capital cost of the lighting system (less funds recovered with utility rebates), divided by the annual energy and maintenance cost savings of the new system relative to the incumbent lighting system. For ROI, the ratio of the annual energy cost savings to the capital cost (minus utility rebates) was multiplied by 100%.

The simple payback was estimated and ROI for various configurations of parameters discussed in the previous sections. All scenarios took into consideration the wide variation of energy costs across the United States. Simple payback and ROI were provided for energy costs of $0.11-$0.12/kWh (Fort Collins summer and winter rates), $0.216/kWh (New York, NY), $0.322/kWh (San Francisco, CA), and $0.477 (San Diego, CA).

Table 20 provides the simple payback and ROI using a fixed lifecycle of 20 years and Xcel Energy as the rebate provider.

Payback periods also varied widely depending on the lighting application scenario and the cost of electricity. Considering the electricity rate in Fort Collins (the first payback and ROI column in **Table 20**), the payback periods ranged from 5.5 years (College Ave. Area Lighting RS1/RS2) to 15.5 years (College Ave. Roadway Lighting RS2).

Table 21 provides the simple payback and ROI using a fixed lifecycle of 20 years and Fort Collins Utility as the rebate provider.

Payback periods varied widely depending on the lighting application scenario and the cost of electricity. Considering the electricity rate in Fort Collins, (the first payback and ROI column in **Table 21**), the payback periods vary from 3.8 years (College Ave. Area Lighting RS1) and 14 years (College Ave. Roadway Lighting RS2).

Table 20: Payback period (in years) and return on investment (ROI) for various electricity costs, a fixed lifecycle of 20 years, and Xcel Energy as the rebate provider (prescriptive rebate).

	Lifecycle = 20 years				Rebate Provider = Xcel Energy			
Scenario	**$0.11-$0.12/ kWh**		**$0.216/kWh**		**$0.332/kWh**		**$0.477kWh**	
	Payback	**ROI**	**Payback**	**ROI**	**Payback**	**ROI**	**Payback**	**ROI**
Model high school: RS1 (80% dim)	6.5	15%	4.4	23%	3.2	31%	2.4	42%
Model high school: RS2 (80% dim)	6.0	17%	4.0	25%	2.9	35%	2.1	47%
College Ave: RS1 (Roadway | 50% dim)	14.2	7%	8.7	12%	5.9	17%	4.3	23%
College Ave: RS2 (Roadway | 80% dim)	15.4	7%	9.2	11%	6.2	16%	4.5	22%
College Ave: RS1 (Area | 50% dim)	5.5	18%	3.4	29%	2.4	42%	1.7	59%
College Ave: RS1 (Area | 80% dim)	5.5	18%	3.4	29%	2.4	42%	1.7	58%
College Ave: RS1 (Decorative | 50% dim)	11.1	9%	7.8	13%	5.8	17%	4.3	23%
College Ave: RS1 (Decorative | 80% dim)	14.6	7%	10.0	10%	7.3	14%	5.4	18%

Table 21: Payback period (in years) and return on investment (ROI) for various electricity costs, a fixed lifecycle of 20 years, and Fort Collins Utility as the rebate provider (custom rebate).

	Lifecycle = 20 years				Rebate Provider = Fort Collins Utility			
Scenario	**$0.11-$0.12/ kWh**		**$0.216/kWh**		**$0.332/kWh**		**$0.477kWh**	
	Payback	**ROI**	**Payback**	**ROI**	**Payback**	**ROI**	**Payback**	**ROI**
Model high school: RS1 (50% dim)	5.7	18%	3.9	26%	2.8	36%	2.1	48%
Model high school: RS2 (80% dim)	5.1	20%	3.4	30%	2.4	42%	1.8	56%
College Ave: RS1 (Roadway | 50% dim)	12.9	8%	7.8	13%	5.4	19%	3.9	26%
College Ave: RS2 (Roadway | 80% dim)	14.0	7%	8.4	12%	5.7	18%	4.1	25%
College Ave: RS1 (Area | 50% dim)	3.8	26%	2.4	42%	1.7	61%	1.2	84%
College Ave: RS1 (Area | 80% dim)	3.9	25%	2.4	41%	1.7	59%	1.2	82%
College Ave: RS1 (Decorative | 50% dim)	10.3	10%	7.2	14%	5.3	19%	4.0	25%
College Ave: RS1 (Decorative | 80% dim)	13.8	7%	9.4	11%	6.9	15%	5.1	20%

In all scenarios, the control system reduced the payback period, though the absolute reduction varied depending on the rebate provider, electricity cost, and lighting application scenario. **Table 22** shows the total power demand and total capital costs associated with each scenario for both applications.

Table 22: Power consumption and capital costs comparisons of Retrofit Scenario 1 and 2.

Scenario	**Total Power**			**Total Capital Cost**	
	Demand [kW]	**ΔPower [kW] (to base)**	**%ΔPower (to base)**	**Cost ($)**	**ΔCost (to RS1)**
Model high school: Base Case (HID)	24.41	-	-	-	-
Model high school: RS1 (50% dim)	12.35	-12.061	-49%	$100,926	-
Model high school: RS2 (80% dim)	9.81	-14.60	-60%	$103,162	$2,236
College Ave: Base Case (Roadway)	2.76	-	-	-	-
College Ave: RS1(Roadway | 50% dim)	1.67	-1.086	-39%	$13,607	-
College Ave: RS2 (Roadway | 80% dim)	1.49	-1.27	-46%	$16,767	$3,160
College Ave: Base Case (Area)	5.40	-	-	-	-
College Ave: RS1 (Area | 50% dim)	1.60	-3.8	-70%	$16,372	-
College Ave: RS22 (Area | 80% dim)	1.85	-3.56	-66%	$16,372	-
College Ave: Base Case (Decorative)	5.66	-	-	-	-
College Ave: RS1 (Decorative | 50% dim)	3.12	-2.54	-45%	$35,514	-
College Ave: RS2 (Decorative | 80% dim)	2.80	-2.86	-51%	$49,686	$14,172

Cost Calculator

All calculations in this section were performed with a custom calculator built in Microsoft Excel.

Download Cost Calculator

5. Discussion

Lighting Design and Application

Light pollution findings for the model HS suggest that the main driver of improving light pollution performance is project design that lowers fixture light output to minimize overlighting and reflected light leaving the site while meeting, but not exceeding, best practice requirements. Choosing fixtures with low U Ratings and using shielding is valuable for reducing sky glow and light trespass at the property boundaries, but minimizing overlighting has a larger impact. This aligns with the DLC's Seven Strategies to Minimize Negative Impacts of Outdoor Light at Night resource, which emphasizes that the most effective light pollution strategies enable controllability and reduce overlighting.

Where the existing pole locations need to be used, such as in a retrofit, there are tradeoffs between meeting illuminance, uniformity, power demand, and light trespass requirements. The MLO and the Fort Collins Lighting Ordinance have low G Rating requirements (G2 Rating) within Lighting Zone 2 (LZ2), which could only be achieved with lower lumen output fixtures. Using these fixtures on existing poles resulted in a situation where the design could either meet the illuminance requirements or comply with the lighting ordinance. In this case, fixtures with higher G Ratings had to be used in many instances to meet the minimum illuminance requirements with existing poles.

AGi32 was used to compute the light pollution quantities related to compliance with the MLO, taking advantage of the convenience of performing these calculations alongside other photometric performance calculations typical in lighting design. Since AGi32 can't perform spectral calculations, estimates of the spectral impacts of light pollution (such as RSG) require a separate software tool (in this case, a Pacific Northwest National Lab Excel calculator).

As expected, there were meaningful differences between the application scenarios with regards to light pollution and power demand performance. Comparing light pollution performance using both the MLO photometric quantities and RSG led to new insights that weren't necessarily obvious previously. For the model HS application, RS1 was worse than the Base Case due to an increase in blue-violet radiation from the 4000K fixtures, despite a small reduction in offsite lumens. For the model HS, RS2 resulted in reduced sky glow and light trespass due to lower light levels and better optical control, including the use of house-side-shields and lower CCTs (i.e., less blue-violet radiation) compared to the Base Case and RS1.

For College Ave., the results are mixed when comparing light pollution performance using both the MLO metrics and RSG. Using the roadway fixtures, RS1 and RS2 were worse due to HPS being used for the Base Case (RSG=1.0). There was some reduction in light pollution in RS1 due to lower U Ratings and reduced light levels, but this was superseded by spectral impacts of using 4000K fixtures. Light pollution performance was slightly better for RS2 compared to RS1, due to switching to 3000K fixtures, but there was still more sky glow due to increased short-wavelength scatter with these LEDs compared to HPS. If all else were equal in terms of fixture performance, using 2200K fixtures in RS2 may have reduced sky glow by an additional 25%, but it would still be slightly worse than using HPS due to a higher RSG. There was also no potential to further reduce the light levels in RS2 due to strict safety considerations for illuminating roadways and existing light level requirements of the Larimer County Urban Street Lighting Standards (2021).

Using area-style fixtures for the College Ave. site reduced light pollution slightly in RS1 compared to the Base Case Condition for two reasons. First, the Base Case used metal halide lamps (RSG=2.5), and 4000K LED fixtures had only slightly higher RSG values (RSG=2.7). These slightly higher RSG values were offset by the slightly lower light levels achieved in RS1 and the use of modern LED fixtures that had slightly different distributions even with equal U0 ratings. Light pollution performance (based on the MLO and RSG) was better for RS2 compared to RS1, due to using a 3000K LED fixture with a lower RSG, even though a higher output fixture was required for equivalent photometric performance to compensate for using a lower CCT. And, as described above, safety considerations for illuminating roadways and existing light level requirements prevented reduction of light levels in RS2.

Using decorative-style fixtures for the College Ave. site, light pollution performance improved for both RS1 and RS2 compared to the Base Case Condition (assumed to be metal halide with an RSG=2.5) but was worst overall compared to other fixture types among all scenarios. All three decorative scenarios failed the MLO criteria for the top plane, including RS2.

Although the RS1 decorative lighting fixtures had higher RSG values (RSG=2.7) and the same U Ratings compared to the Base Case fixtures, their lower light output reduced the (high) sky glow by 2%. Sky glow performance improved significantly for RS2 compared to RS1 and the Base Case due to the use of 3000K fixtures (RSG=2.2), U0 ratings, and lower light output fixtures.

While the illuminance and uniformity results were similar in all application scenarios for the model HS, the power demand was, as expected, reduced significantly for the RS1 scenario (compared to the Base Case Condition), which focused on energy efficiency alone. The power demand was reduced further for the RS2 scenario due to lower light levels, which was also the main factor in reducing light pollution.

Another key lever enabling power demand and light pollution reduction in both applications (model HS and College Ave.) was the use of controls. Compared to no dimming for the Base Case scenario, dimming the fixtures down to 50% of full power for RS1 and dimming down to 20% of full power for RS2 was effective in further reducing light pollution. However, this strategy has cost implications, which are discussed below.

As expected, energy usage was reduced significantly for RS1 compared to the Base Case scenario, among the model HS and College Ave. scenarios, which focused on energy efficiency alone. The results for RS2 were somewhat mixed. In the model HS application, RS2 fixtures reduced power demand by an additional 20.86% compared to RS1. In the College Ave. application, power demand was reduced by 11.1% and 10.3%, respectively, in RS2 compared to RS1 for the area and decorative fixtures. With area fixtures, however, power demand increased in RS2 due to needing higher power fixtures to meet the same light level requirements because of the lower light outputs at 3000K.

Cost Analysis

Many factors influence the simple payback and ROI calculations on an installed LED lighting system. At minimum, these include the capital cost, potential inflation of capital costs, markups on the capital cost through distribution, local sales tax, installation costs, available rebates, maintenance costs (replacements, labor, and cleaning), energy costs, and control schedule (resulting in additional energy savings).

The cost analysis shows that, in all cases, the College Ave. application using roadway and decorative-style LED fixtures had significantly longer payback periods than the retrofit scenarios at the model HS or the retrofit scenario at College Ave. using area fixtures. This is primarily due to the following reasons:

- The decorative fixtures had a much higher per-unit cost than other fixtures, and more fixtures were needed to achieve the same photometric performance as the Base Case scenario.
- The decorative and roadway fixtures provided proportionally lower power reductions (relative to the Base Case) than did the area and model HS fixtures; resulting in lower overall energy cost savings and an overall longer payback period. Due to the lower power reduction, these fixtures benefitted less from rebates that are tied directly to the amount of reduced power.

In this study, the application scenarios included relatively few fixtures (between 5 and 84 fixtures, depending on the application scenario) compared to the total capacity of the Acuity nLight Air control system, which can control up to 150 fixtures. This meant that the project incurred the full cost of the lighting control system without using it to its full capacity, and therefore the lighting control system was a significantly large proportion of the total capital cost of each retrofit scenario (between 16% and 52%). The payback periods are expected to be shorter in larger lighting application scenarios where the cost of the lighting controls system is distributed across more fixtures.

In all the retrofit scenarios considered for the model HS application, RS2 provided a shorter payback period than RS1. This suggests that RS2, which aligns with the DLC's Seven Strategies to Minimize Negative Impacts of Outdoor Light at Night, provides additional benefits due to lower light levels (and lower power demands) and deeper dimming, despite the higher total capital costs (see **Table 22**).

In comparison, the payback periods in the College Ave. applications weren't always shorter in the RS2 scenarios, compared to RS1.

- In the roadway retrofit of College Ave., RS2 had a longer payback period than RS1 (incumbent LED specification). The longer payback period was driven by a large increase in capital cost (proportional to the capital cost of RS1) with only a modest decrease in energy consumption (see **Table 22**).
- In the area lighting retrofit of College Ave., RS2 had a slightly longer payback period than RS1. These slightly longer payback periods were driven by a slight increase in energy consumption of RS2 versus RS1, with no change in capital cost (see **Table 22**).
- In the decorative lighting retrofit of College Ave., RS2 had significantly longer payback periods than RS1. The longer payback periods were driven by a very large increase in capital cost (proportional to the capital cost of RS1) with only a modest decrease in energy consumption (see **Table 22**).

Lessons Learned

This study revealed several potential strategies for decreasing payback periods and increasing ROI, and highlighted several issues to consider going forward, including:

1. Capital cost is a significant factor in the length of the payback period and ROI. The lighting applications in the study used a small number of fixtures, which are presumed to mean higher per-unit cost. Bulk unit pricing may be able to reduce capital costs and decrease payback periods.
2. The lighting control system cost is most tenable where its cost is proportionally small in comparison to the total capital cost of the lighting system. If each fixture provides cost savings relative to the incumbent lighting system, payback period will be decreased with more fixtures (all else being equal).
3. During this project, some lighting control equipment manufacturers were not interested in providing a control system for fixtures they do not manufacture due to possible compatibility issues. Taking this claim at face value, compatibility issues have the potential to result in longer payback periods and ROI. Fixtures cannot incur incremental energy cost savings if they are not dimmed.

6. Conclusion

Many factors influence the light pollution performance of an outdoor retrofit LED lighting system. Each of these factors requires careful consideration in the design and application of outdoor LED retrofit system, as they will impact system performance, payback period, and ROI. The factors include optical distribution of fixtures, the use of shields (such as house-side-shields), site configuration and reflectances, illuminance and uniformity criteria, light source efficacy, minimizing overlighting, the use of lighting controls and implementable lighting control strategies, spectral characteristics of fixtures, limiting factors of the retrofit (e.g., pole locations, local ordinances), and cost and availability of fixtures.

Light Pollution Mitigation

Due to lower CCTs (and thus lower RSGs) and low U Ratings, LUNA-eligible and LUNA-qualifying fixtures were able to reduce light pollution impacts compared to DLC SSL V5.1-listed LED fixtures (RS1) for all application scenarios that were investigated. The two main metrics used in this project to quantify light pollution were lumens leaving the site (calculated per the IES/IDA MLO) and relative scotopic sky glow due to spectrum (RSG). Offsite lumens are the aggregate of the direct light emitted from a fixture (uplight above 90 degrees and downlight crossing the property line) and light reflected from the ground and adjacent buildings. This study demonstrates that reflected light had the most significant impact on sky glow followed by direct uplight.

Energy Efficiency

As expected, energy efficiency increased significantly in all applications using DLC V5.1-listed LED fixtures in RS1, and, in most cases, increased further in RS2, which also reduces light pollution.

In the College Ave. application, energy use was incrementally reduced within the RS2 iterations with roadway and decorative fixtures but increased with the area fixtures. The findings suggest that the use of LUNA-eligible (and LUNA-qualifying) fixtures for roadway applications can result in incremental energy savings when less light is wasted (e.g., if the uplight component of the fixtures is reduced, and/or if more efficacious fixtures are selected, and/or if overlighting is avoided). However, the design may also result in equal or increased energy use if there is no opportunity to minimize overlighting or if the fixtures are less efficacious at lower CCTs.

Payback Periods

The model high school (HS) application scenarios revealed that a retrofit focus using LUNA-eligible fixtures (RS2), along with minimizing overlighting and utilizing deeper dimming, resulted in a shorter payback period than a retrofit that focused on using energy efficiency alone with DLC V5.1-listed LED fixtures (RS1). This was enabled by a proportional reduction in energy consumption (compared to RS1 and the Base Case), with only a marginal cost increase.

The economic analysis of the College Ave. application scenarios showed that the payback period for RS2 was equal to or higher compared to the RS1 depending on the fixture type, controls costs, energy rates, and rebate amount. The difference in payback periods was small for area lighting fixtures (0.0 – 0.1 years), larger for roadway lighting fixtures (0.2 – 1.1 years) and largest for decorative lighting fixtures (1.1– 3.5 years). In this application (a main street with multi-lane roadway and parking), using LUNA-qualifying fixtures may not always result in incremental cost savings compared to using products that focus on energy efficiency alone. Municipalities must be sensitive to the realized energy savings relative to the increased cost of fixtures. In some scenarios, savings will work out such that using LUNA-qualifying fixtures is the obvious choice, as in the area lighting scenario. However, the decorative scenario would not be cost effective without incremental incentives or considering the non-energy benefits.

While adding a networked lighting control system was advantageous in terms of energy usage, the system selected was not a cost-effective option in the small-scale applications that were considered, and it increased the payback period of the overall lighting systems. For larger installations, the use of networked lighting controls may be more justified. A further investigation can be conducted in the future to determine if dimming to 20% at night can be achieved by a less expensive control system that would result in overall cost savings.

Dimming Impacts

For both the model HS and College Ave., using controls that dim the fixtures to 20% of full power during the night when the space is unoccupied, beyond the 2019 energy code requirement of 50% of full power, resulted in incremental light pollution reductions and energy savings. This capability is a requirement for LUNA qualification.

While this study did not investigate implementing high end trim with the installed NLCs, this strategy will enable further energy savings and light pollution reductions if light levels can be further reduced.