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Universitat Autònoma de Barcelona

Facultat d'Economia i Empresa UAB

Final Degree Project

Faculty of Economics and Business

Title: Lighting the Way: A Cost-Benefit Analysis of LED Adoption in Barcelona's Public Lighting Infrastructure.

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1. Abstract

This final degree project presents a comprehensive Cost-Benefit Analysis evaluating the socioeconomic viability of transitioning public lighting infrastructure from traditional High-Pressure Sodium (HPS) lamps to modern Light-Emitting Diode (LED) technology, using the municipal network of Barcelona as a case study. Operating within a 10-period framework, the study designs and evaluates three policy scenarios: Project A (accelerated full implementation in the first period), Project B (a phased rollout over five periods), and Project C (the status quo baseline of maintaining the existing HPS system). Following the HM Treasury Green Book guidelines, the Social Time Preference Rate (STPR) is derived under two real economic growth assumptions (1.5% and 2.0%), yielding discount rates of 3.0% and 3.5%, respectively. The analytical model incorporates direct expenditures; including fixture procurement, anti-corrosion poles, installation, energy prices, and operational maintenance costs; alongside quantified social variables, specifically crime reduction, traffic accident mitigation, and the negative public health externality of sleep deprivation caused by melatonin suppression. The empirical results demonstrate that Project A is the unique socioeconomically viable strategy, generating a substantially positive net present value (NPV). Conversely, the phased approach in Project B underperforms the status quo baseline due to prolonged structural inefficiencies and deferred social benefits. Sensitivity tests were conducted to try to see the impact of certain measures such as the cost of sleep deprivation. The results yielded from these tests still put Project A at the forefront and make it so that Project B beats the baseline. The study concludes that rapid, front-loaded public investments in energy-efficient infrastructure maximize public welfare, offering key policy implications for local administrative decision-making.

1.1. Keywords

Cost-benefit analysis: Analysis done on public infrastructure projects to see their viability.
LED street lighting: Street lighting infrastructure that utilizes LED technology
Public infrastructure: Infrastructure that is provided and administered by government bodies.
Social Time Preference Rate: Rate at which society discounts time.
Barcelona: Largest city in the Catalonia region of Spain.
Crime reduction: Reductions in legally punishable offences.
Road traffic accidents: Accidents and injuries associated to motor vehicles and road elements.
Melatonin suppression: Diminish of quantity of melatonin in the body due to external factors.
Energy efficiency: Optimisation of use of energetic resources.
Urban policy: Policy conducted in urban areas.
Public welfare: General welfare of a society.
Sleep deprivation: Alteration of sleeping patterns resulting in lack of sleep.

1.2. Abbreviations

CBA: Cost-benefit analysis

LED: Light emitting diode

HPS: High pressure sodium

LPS: Low pressure sodium

UK: United Kingdom

US: United States of America

2. Acknowledgments

The development of this project has been a very long and careful process and hence I have to give thanks to all the people who have helped me.

First I would like to thank my friends and family who have always given me their complete support. I want to thank them for their ideas for the realization of this project which have been very helpful at times when I found myself in need of a different perspective.

I would like to make a special note for my roommates who are both studying the degree of Economics in the UAB, and it is with them that I have debated and asked their opinion the most throughout this whole process. There were times when I required a quick educated opinion on something, and they were always at the ready to provide assistance and their knowledge completely to my service, and for that I want to give them a very profound "thank you" to both.

Last but certainly not least, (and in hopes of not sounding too much like the teachers pet) I would like to thank my tutor Miguel Ángel Lopez Garcia. The amount of support and dedication he has put into helping me with this project is worthy of praise. There has not been a moment where he did not provide a thoughtful analysis, clear guidance, detailed response or sincere encouragement. Having already had him as a professor for 2 consecutive terms I could not be happier that he is my tutor. I sincerely consider him one of the best professors I have ever had in all of my years being a student (at every level) and I feel he gets very little praise from my peers in this sense. Some might say he can be a bit demanding, but to me that is what a good professor does. From the bottom of my heart thank you very much.

3. Introduction

Public lighting has been around for a long time. There are records of Ancient Greece and Rome that show early adoptions and iterations of different styles of lighting for the public space. This is not surprising at all, light is essential for nearly all forms of life in this planet, and it is even more essential for the correct functioning of a civil society.

The methods and infrastructure surrounding this vital element of modern society have changed dramatically over the centuries. Back in Ancient Rome, oil lamps were the preferred option when it came to lighting the dark corners of the world, this was mainly due to the duration of oil and the moderate flame it emits when being burned. Higher class "patricians" had vast displays of oil lamps around their villas, which were changed everyday by a specific slave named the "*lanternarius*".

As mentioned previously this was mainly reserved for those who could afford it, and when street oil lamps were used in a broader public setting this would be for an event such as a festival or gathering of some sort. The majority of people relied on what was known as "link boys" which were men who carried around oil lamps and escorted people around in the dark for a fee. In other places, such as Pompeii, white stones were engraved into the pavement in order to reflect moonlight and improve overall visibility in the night hours.

However, it wouldn't be until the 13th century when the first instances of a public network of lights began being introduced. There are some records which indicate that London was the first city to have a proper street lighting system which relied on candles and a "lamplighter" which went around the city at dusk, lighting up the candles. It is said that this was ordered in 1417 by Sir Henry Barton, Mayor of London, and it might be the first recorded instance of a public streetlight infrastructure, though the veracity of this is still being debated.

From here the concept started to spread across Europe, and it was adopted by several countries with different iterations and improvements on the design such as better glass for the lamps and different sources of fuel.

It wasn't until the 4th of June 1807 when the first demonstration of a gas network of streetlamps was carried out in Pall Mall, London. This network closely resembles what we have today, an automatic and continuously supplied network of streetlamps. From here, the concept started spreading once again across Europe to cities like Paris, and it became an absolute necessity for any modernizing city.

As the industrial revolution started to pick up speed during the end of the 19th century and electricity became more common, the first electric streetlight were adopted and continued to be adopted as more inventions in the way light was produced were being made. Such is the famous case of Thomas Edison and his revolutionary light bulb and many others who were on the cutting edge at the time.

By the end of World War 2 the adoption of street lighting was very widespread amongst the more developed countries, this was also the time were street lighting began to take the form that we are most used today, which is that of Low pressure sodium (LPS) lamps that emit this yellowish glare that we are so familiar with today. Towards the end of the 20th century, the lights were changed for High-pressure sodium (HPS) lamps, which do the same job as the Low-pressure but are brighter and last longer.

Finally, when we get to the 21st century, a new development in the streetlight technology has taken place and that is off course the start of the adoption of LED lights in the public lighting infrastructure and how these lights have revolutionized a part of infrastructure that many had thought to have reached its most refined version already. These lights are said to consume around 60 to 80% less energy than previous High-pressure sodium lamps and provide a much better visibility aspect as well.

Taking a look back, it is easy to draw some conclusions out of humanity's history with public lighting. Lighting has been a sign of development and status ever since the Ancient Greek and Roman times; the benefits that better lighting brings are obvious in many aspects and not so in others, but this will be developed later on.

Last but not least, the adoption of better technology when it comes to public lighting has been rather fast across of human history, and it only has gotten faster. This raises many questions surrounding what is currently being done with this key part of infrastructure.

In this project, I will be taking on the task of analysing the overall costs and benefits the improvement of the lighting infrastructure has, and if these improvements are being carried out fast enough by governments across the world. This last part is rather important in the sense of a hypothesis, as some could argue that the benefits of improving the lighting infrastructure are so big that taking long on doing so is just a terrible waste of resources.

For this analysis, I plan to carry out a detailed accounting of the cost and benefits this type of infrastructure brings to society and what are the key areas where focus should be drawn to. To do this I will be taking data from countries and cities where this has been carried out already, and I will be trying to give some policy advice and analysis to the city I currently live, Barcelona, which is also currently undergoing the transition from HPS lamps to LED.

4. Project framework

To carry out this analysis I will be creating three different scenarios which will be used to see the different impacts the project has across different time periods. For this I will be doing my analysis in a 10 period framework. I will be assuming that each period corresponds to a natural year and that the projects will be carried out as planned by the administration that is responsible.

First, what I will be calling Project A will take into account that the project will be carried out as fast as possible. This scenario is meant to try to capture the effects that the implementation of LED streetlights will have if the governing body takes it as an absolute priority. In this scenario, I will assume that the full investment of the project is carried out in the first period and will be completed by the end of period 1. Meaning that the costs of installation and changes in infrastructure are paid in full by the end of said period. This is meant to help see how much of a burden is placed in placing such high priority on the changing of the street lighting infrastructure; and if the benefits obtained from doing this in such a rapid fashion outweigh the costs of bearing the installation in just one period.

Secondly, for what I will be calling Project B, I am going to distribute the costs of installation and the speed at which it is done over the first 5 periods. This is meant to serve as a counterpart of Project A to see whether if giving a bit less priority to the project makes it easier to bear the costs. In addition to that, project B is useful to analyse the different gains and losses that come with the slower implementation of the LED streetlights.

Finally, Project C will serve as a control. Where the implementation of streetlights will not be carried out. This is in order to provide a good countermeasure and overall view of whether the undertaking of such an infrastructure modification makes socioeconomic sense.

4.1. The social time preference rate

Carrying out a cost benefit analysis always requires an appropriate discount rate. As this analysis is being carried out in the short to medium term there will be no need to utilize declining long term discount rates. This implies that a single rate can be used and not have it affect the analysis.

With this in mind, I will still be providing different calculations of rates to try to be as precise as possible in order to provide a solid framework for the possible changes the economy might face along the periods.

The criteria I will be following for the calculation of the rates will be that of the HM Treasury Green Book, which still remains one of, if not the most, relevant public project appraisal guidelines in most of public economics.

The formula used in the book is the following:

$$STPR = \rho + \mu . g$$

Where ρ stands for "the rate at which individuals discount future consumption over present consumption, on the assumption that no change in per capita consumption is expected". This parameter is composed of two separate elements which measure "Catastrophe risk" and the "Pure time preference".

The catastrophe risk measures the "likelihood that there will be some event so devastating that all returns from policies, programmes, or projects are eliminated, or at least radically and unpredictably altered."

The pure time preference, as the name suggests, measures the preference of individuals for consumption now rather than later without changing the level of consumption per capita over time.

The components on the right-hand side of the equation represent the elasticity of marginal utility of consumption (μ) times the annual rate of growth of the economy (g).

Having established the methodology that is going to be used for the calculation of the STPR, I will proceed to derive the different rates that are going to be used for the project and explaining the reasoning behind choosing said parameters. These parameters will be taken from previous studies as it would go way beyond the scope of this project to try to do them myself.

First, when it comes to estimating the ρ there are a few different estimates that oscillate the value of ρ between the 0.5, Drupp et al. (2018), and 1.5, Scott (1977). The different methodologies used for the calculation of these values make it so that the variation is quite high. For this reason I will be deciding on the estimate provided by Scott (1989) which puts the value of ρ around 1.3. This is also in order to not overestimate the possible risks that a project like this one might have. Usually when considering public infrastructure projects one has to take into account possible accidents which in many cases could be catastrophic, and off course this is not the exception. However, one might also argue that the overall risk being taken in this case is not as great as other infrastructure works such as the construction of a new dam, highway, or metro line.

Moving on to our estimate of the elasticity of marginal consumption (μ), some studies analysing revealed preference from progressive taxation such as the one done by Groom & Maddison (2019) put it around 1.5. In the Green Book the estimate that is used is 1, and it is derived from Pearce and Ulph (1995) were they got a range from 0.7 to 1.5, that together with Cowell & Gardiner (1999) and OXERA (2002), makes the HM arrive at the consensus of 1.

For this analysis I will be taking the Green Book value of 1 as my estimate of the elasticity of marginal consumption. It is the one that has the biggest consensus surrounding it, and it also makes sense when putting it into the context of the projects. Street lighting is relatively uniformly enjoyed by the different segments of society in a city. If we were to change the scope of the analysis to a broader more national level things might change, for now 1 will have to do.

Last but not least we arrive to our estimate of growth (g). This is where the territory starts getting a bit less stable in the consensus surrounding it. Estimating growth is one of the hardest things to do in economics, the amount of variables that need to be taken into account is no short of daunting. This is why I will be using different scenarios of growth to try to capture the impact that the project may have in different economic conditions. The Green Book uses the 2% standard objective by most developed economies as its estimate of growth (Mainly derived from Maddison 2001). This is also consistent when looking at the long term growth rates of real GDP in countries like the US. This is not a bad approach in of itself but when looking at data in recent years and with current world events one might think that it might start to look a bit too optimistic. Real GDP growth rate has been below the 2% mark in the past 10 years in both the US and the EU. IMF and OCDE estimates place future growth around the 1.5% to 1.8% mark. To try to capture the different possible growth prospects I will be utilizing both the 2% and 1.5% estimates in order to produce 2 social time preference rates which reflect favourable and underwhelming growth estimates.

Finally, we get to the calculation of the STPR's:

$$STPR_1 = 0.015 + 1 * 0.02 = 3.5\%$$

$$STPR_2 = 0.015 + 1 * 0.015 = 3\%$$

Having done the first crucial step to the cost benefit analysis I will proceed to the accounting and provision of the different costs and benefits associated with the installation and impacts that LED streetlights bring.

5. The costs

I will start this accounting of costs from our current baseline which is Project C. According to private providers such as “Honnex” and “Logoslighting” the installation cost per unit of an HPS lamp is between approximately 150–450 euros. Taking into account that the lamp posts are also acquired (I will be taking the average of this number in order to try to be as realistic as possible). Adding to this we have that the maintenance costs that is done periodically during the period is around 100 euros per lamp.

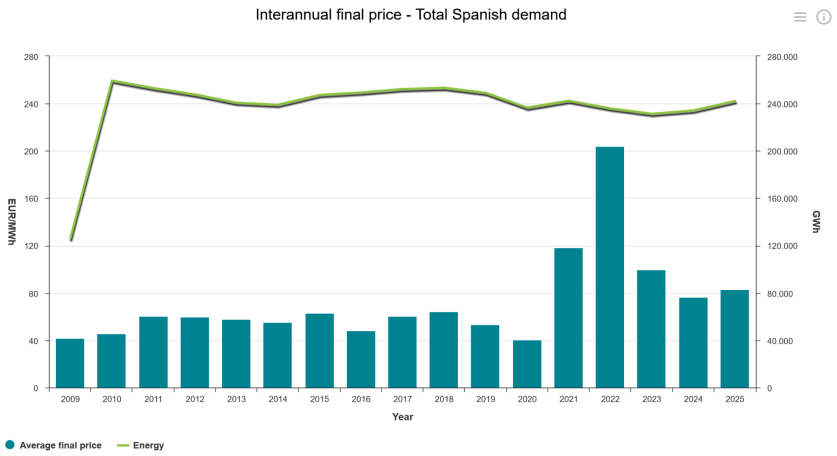
Being this the baseline case we start from a point were HPS lights have already been installed and so the initial cost of installation is not needed. Having stated this, we have to take into account that these lights are not long-lasting. Typically, HPS lamps have a lifespan of 15,000 to 24,000 hours; assuming that streetlights are lit for around 12 hours a day, this puts the life span between 3.5 and 5.5 years. To make calculations easier I will be taking the average of the estimates, so this would mean that every 4 periods the streetlights need to be replaced.

As mentioned previously in the framework of this project, I will be basing this analysis in the city of Barcelona, so for the size and scope of the costs I will be taking data directly from the Ajuntament’s website. Here it is stated that the number of streetlights in Barcelona is estimated to be 157,000. In order to try to emulate the most accurate representation of reality I will be assuming that the streetlights don't have to be replaced all at once every 5 years. Instead, I will be assuming that every period there will be around 10% that need to be replaced. This sets the number of lights to be replaced to 15,700 per period. It can be argued that this is not as realistic as I am not taking into account when were the majority of the lights installed or the variability that some lamps may give out before their time is due. However, this would elevate the complexity of this project dramatically and the effects wouldn’t be too different from the ones we may get from the standardized calculations.

One of the most vital parts of the analysis is without a doubt energy prices. For this I have to calculate how much each light bulb consumes in energy and what that represents for the analysis. HPS lamps have an average consumption of 250W, this means that for every hour that the light is turned on their needs to be 250W supplied. So for 4 hours of consumption that would mean that the lamp has consumed 1000W/h. I will be using Kilowatts instead of Watts as it is the standard when measuring energy prices. For all calculations I will be taking the average of the price of the energy in Spain for the last 10 years. The average price obtained is

around 0,085 euros per Kilowatt-hour. Now that all the costs are accounted for I would clear a few things.

Figure 1: Energy prices from 2009-2025



Source: Nominated Electricity Market Operator (NEMO or OMIE in Spanish)

As this is the baseline case, any indirect costs associated will be taken as if they are already taken into account by consumers and do not affect the overall calculation. This mainly done in order to provide a solid base for the analysis of the LED lights to take place in; as being able to point out outliers and differences between the two is key when trying to understand fully what each option brings to the table.

Last but not least, we have to account for some of the indirect costs that LED technology and, artificial lighting in general, brings into the public space. Recent studies have shown how the higher intensity blue-light-filled LED lights cause a bigger disruption in circadian rhythms in human beings and other animals. This is due to how the body misinterprets the light as being natural and kicks inner systems to wake up the body when it should be preparing itself for sleep. This may not seem big, but studies estimate that sleep deprivation wipes out around 1.9% to 2.9% GDP in the US each year. For other countries such as Germany and the UK it hovers around 1%-1.6% and 1.4%-1.8% respectively.

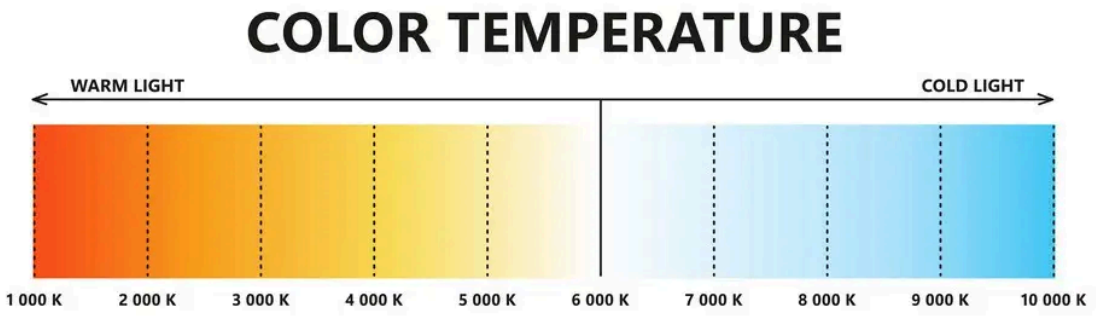
These are some huge numbers and the precision of them may well still be up for debate, but what is not up for debate is that the alteration of sleep cycles have a real impact in socioeconomic activities. It is rather difficult to incorporate this abstract cost in our analysis as it partakes in many variables such as; if people have curtains of full on blind which block out all light, whether lights are at level of houses/flats or they are below them.

We can also extend this problem to animals and the ecosystems that are inside and surround cities. With higher intensity lights it has been shown that bug populations diminish and this may well cause a much bigger impact in the overall ecosystem.

Now when discussing the fragmentation or reduction of sleep many difficulties and quarrels appear all at once. Sleep is vital in the most literal sense of the word, without sleep our bodies simply wither away. But as we all know, different bodies have different tolerances and lack of sleep may severely impact some while not so much others. What is without question is that lack of sleep is in general terms bad for everyone.

What really matters when talking about the impact of light levels on sleep cycles is what studies call the "Melatonin Suppression Index" (MSI) which ranges from 1 to 0 (1 being complete melatonin suppression, 0 being none). This is due to the fact that not all light suppresses melatonin (the molecule that tells our body when we should be feeling like going to sleep) the same way. Warmer light tends to disrupt the body less than whiter light. The spectrum goes as follows:

Figure 2: Range of colour temperature in Kelvin scale.



Source: Ecobriteled.com

Typically, HPS lamps are 2100K and LED range between 3000K and 6000K. For this study I will be assuming that all LED lights are 3000K. This is due to the fact that many studies suggest that the level of warmth of street lights shouldn't surpass the 3000K mark, as is suggested by the Department of Energy efficiency in their reports of "Human and Environmental Effects of Light Emitting Diode (LED) Community Lighting.". The study done by Aubé, M., et al. (2013). "Evaluating the Blue Light Content of Artificial Light Sources in the Context of the Environment and Human Health." calculated the MSI for each of the different levels of warmth and had some interesting findings.

For a typical HPS lamp the MSI is around 0.10, as done previously with most things concerning our analysis of HPS lamps this will be the baseline. For warm LED lights of

3000K the study gives an MSI range of 0.20-0.25 and for levels higher that 4000K and above the values start growing exponentially ranging from 0.35 to 0.50.

In order to relate this to the analysis of cost I will be taking the value found in the 2018 study done by Mathew Gibson and Jeffrey Schrader on "Time use and labor productivity: The Returns to Sleep". In this study they find that the wage elasticity of sleep is around 0.011, which means that for every hour of sleep lost there is a 1.1% loss in wage for the average worker. For all of this to make sense I will be constructing a small model that relates all of these values and variables and puts it into monetary terms to be able to add them to the accounting of costs.

$$Cost\ of\ sleep\ deprivation\ per\ period = P_t \times \left(S_L \times \varepsilon\right) \times W_{Avg}$$

P_t: Exposed population at time t

S_L: Daily sleep lost in hours which is calculated as:

0.05 hours x (Proposed MSI / Baseline MSI)

ε: Wage elasticity of sleep.

W_{Avg}: Average annual wage of the population.

This formula will help to bring the abstract costs of lack of sleep back into the analysis. One thing worth clarifying is the assumption that is being done with the daily sleep lost function and that is that the baseline sleep lost is 0.05 hours per night. This is in order to stay consistent with studies carried out were the impact of light on sleep was measured in different populations and with some estimations I chose to use the average of 0.05 hours. Another thing worth noting, is that the impact of light on sleeping cycles varies quite a lot with things such as floor height or the presence of blinds. I decided to take the simpler option of assuming it affects everyone equally; not only due to its simplicity but rather due to the fact that this measure is an upper-bound social penalty where I make sure that no possible public health risks are ignored.

The projects being modelled after the city of Barcelona I will be taking the population records from the "Instituto Nacional de Estadistica" which estimates the population to be around 1,731,000 people. The average wage I will be taking from the statistics website provided by the "Ajuntament de Barcelona" which estimates it to be for 2024; 36,466 euros annually.

5.1. Cost per period in Project C

First and foremost, we are assuming that every period 15,700 lamps have to be replaced. Without average of 300 euros per lamp this means that we have 471,000 euros every period spent on replacing HPS lamp bulbs. On top of this, each one of the 157,000 lamps need to be maintained. This ends up costing 1,570,000 euros per period. All the 157,000 lights are assumed to be on for 12 hours each day of the 365 days in one period. This means that all the lights are turned on for 4380 hours each period and consume 0.250 Kilowatt/hour, which gives us that every period there is an estimated energy consumption of 14,612,775 euros per period.

Finally, one should not forget to account for the indirect effects of light on sleep deprivation, being this the baseline case it will have less of an impact, but it should be accounted for anyway.

$$Cost\ of\ sleep\ deprivation\ per\ period = 1,731,000 \times (0.05 \times 0.011) \times 36,466 = 34,717,455.3$$

Adding all of these costs up leaves us with a per period cost of 51,371,230.3 euros per period. Being this the simplest Project of the bunch when it comes to cost I will be doing the streamline of costs right away with both of the STPR's.

$$Cost\ of\ Project\ C_1: \sum_{t=1}^{10} \frac{51,371,230.3}{(1+0.035)^t} = 427,234,247.3$$

$$Cost\ of\ Project\ C_2: \sum_{t=1}^{10} \frac{51,371,230.3}{(1+0.03)^t} = 438,207,014.4$$

Having derived Project C's streamline of costs it is time to move on to the more substantial part of this cost benefit analysis and that will be the estimation of costs for Projects A and B.

5.2. Cost of LED light installation and maintenance

First I will start by laying out the groundwork for the calculation of the costs that replacing HPS lamps for LED. There are many prices and types of LED lights, you can pick and choose for days and there are still more things you can add. For instance, some suggest that motion detection and light sensors for dimming or increasing the potency of the lights can be added

into each individual pole for better performance and energy saving. This is a marvellous idea, but it goes beyond what we are trying to analyse here as the impacts of having these extras would put this analysis way over its head. It would be necessary to conduct studies on how do these technologies affect everyday life and if they are applicable even.

So for this reason I will be taken the baseline case of just replacing HPS lamps for LED and no extra technology added apart from those needed for their correct functionality. Estimates vary greatly from provider to provider but for this particular case I have decided the 100W LED light for urban roads provided by "Logoslighting" as it is the one that best fits the profile of the project. There are more potent lights available that are meant for highways and stadiums but these obviously are not meant for these projects. The cost per lamp provided is around 400 euros, to that we have to add that these lamps require a different pole than HPS as their light is not 360 degrees and requires proper direction to light where needed. The poles need to be of an anti-corrosion material which usually means aluminium or any other galvanized materials. Costs for this vary greatly as well so I will be estimating it by taking the average from the range provided by "Lightway Traffic" of 1500–2400 euros per pole. This puts us at an average cost of 1950 euros per pole. One thing I would like to add is that in some cases not every pole requires replacement as some newer poles have compatibility with the newer LED technology. With this in mind I still chose to assume that every pole requires changing in order to make the analysis as robust as possible in a hypothetical "worst case scenario".

Another key aspect that needs to be added to the accounting of costs is the installation cost of each lamp. Estimates range between 700 and 1400 euros per lamp, simplifying this would set the installation costs around 1050 euros. We have to add the waste treatment of the previous lamp posts we are replacing which is estimated around 100 euros per pole. All together we have 1150 euros per lamp just from labour costs.

As before, we have to also add maintenance cost per lamp, which in this case is not as high as previously seen with HPS lamps. LED lights require less maintenance per lamp with estimates ranging between 20–50 euros per lamp. To make calculations easier we will say that each lamp has to be maintained for 35 euros each period.

Where the cost of LED lights really shines is in their energy efficiency. HPS lamps cost more than double of what LED lights cost in energy consumption. LED lights need just 100W/h to function instead of the 250W/h of HPS. This provides a huge advantage for LED lights, as we have seen previously in HPS lamps these costs count for the large majority of the infrastructure's cost structures.

5.3. Cost structure of Project A

After this extensive description of the uniqueness of LED lights when it comes to its overt and hidden costs we can finally delve into the actual accounting.

As previously mentioned, Project A carries out the installation of LED lights in the first period. The cost of installation of a single lamp amounts to 3600 euros, this is obtained from adding the different costs previously detailed, lamps, poles, and labour. By multiplying this number by the amount of street lights in our sample we get that the city will be spending just on the installation of these lamps a total of 565,200,000 euros in the first period of the project. Simply seeing this figure we can already tell that the project entails a huge expenditure that already blows out of proportion the whole expenditure carried out in project C.

For 100W lamps we have that 5,845,110 euros are spent each period on energy in order to be able to light up the streets. Additionally, we have that each lamp has to be maintained periodically for 35 euros; which this means a total expenditure of 5,495,000 euros per period.

The cost brought by sleep deprivation each year is:

$$1,731,000 \times (0.1 \times 0.011) \times 36,466 = 69,434,910.6$$

This ends up amounting to a total of 80,775,020.6 euros per year in just energy costs, maintenance and the extra costs brought by the lack of sleep due to the exposure to light at nighttime disrupting melatonin in individuals.

For the calculation of the costs I will be providing the full detail for only one of the STPR's, but I will provide the result for both.

$$Cost\ of\ Project\ A_1: \frac{641{,}129{,}520.6}{(1+0.035)} + \sum_{t=2}^{9} \frac{80{,}775{,}020.6}{(1+0.035)^t} = 1,155,916,348$$

$$Cost\ of\ Project\ A_2: \frac{641{,}129{,}520.6}{(1+0.03)} + \sum_{t=2}^{9} \frac{80{,}775{,}020.6}{(1+0.03)^t} = 1,172,956,604$$

5.4. Cost structure of Project B

Having already done most of the heavy lifting for the cost accounting previously, I am just going to show how the schedule of costs changes as the project is approached more conservatively.

This project will have all the lights replaced at the end of period 5 so period 6 starts of with all lights being LED. Simply dividing the amount of lights in the city by 5 we get the amount

that are replaced each year, which is 31,400 lights each year. Where this project gets a bit tricky is during the periods where there are both HPS and LED lights in the city as I will have to calculate their impact separately and then join them in order to get the full picture.

For this project I will have to calculate different costs for the first 5 periods as the lamps get changed gradually and that affects the energy and maintenance costs. In each of the first 5 periods there is a fixed expenditure of 113,040,000 euros that come from the installation of LED lights. I will show the full procedure for the first period and then just show the results for the rest of the installation periods in order to keep things tidy.

First period calculations:

- LED purchase and installation: $113,040,000\ euros$
- LED maintenance: $31,400 \times 35 = 1,099,000\ euros$
- HPS maintenance: 125,600 × 100 = 12,560,000
- LED energy costs: $31,400 \times 4380 \times 0.1 \times 0.085 = 1,169,022$
- HPS energy costs: $125,600 \times 4380 \times 0.25 \times 11,690,220$
- Sleep deprivation costs:

  $1,731,000 \times \left[\frac{4}{5} \times (0.05 \times 0.011) \times 36466 + \frac{1}{5} \times (0.1 \times 0.011) \times 36466\right] = 41,550,946.36$

  Period 1 costs = 181,219,188.4

The main changes in the calculations compared to the calculations of project A are that there is both sleep deprivation from HPS and LED, and they change proportions as the periods advance and the lights change. Same thing is applied to the calculations of the maintenance and energy costs. Lamps are assumed to be changed at the beginning of the period as to make calculations easier despite this being unrealistic.

Then, once period 6 is reached the costs from installation of lamps disappear and all the costs associated with HPS lamps do as well.

Cost from period 6 onwards

- Maintenance costs: $157,000 \times 35 = 5,495,000$
- Energy costs: $157,000 \times 4380 \times 0.1 \times 0.085 = 5,845,110$
- Sleep deprivation costs:

  $1,731,000 \times [(0.1 \times 0.011) \times 36466] = 69,434,910.6$

Costs per period from period 6 to 10 = 80,775,020

Finally, with these costs the overall cost of the project can be calculated:

$$\frac{181{,}219{,}188.4}{(1+0.035)} + \frac{184{,}368{,}146.4}{(1+0.035)^2} + \frac{187{,}517{,}104.5}{(1+0.035)^3} + \frac{190{,}666{,}062.5}{(1+0.035)^4} + \frac{193{,}815{,}020.6}{(1+0.035)^5} + \sum_{t=6}^{5} \frac{80{,}775{,}020}{(1+0.035)^t} = 1{,}152{,}742{,}346$$

$$\frac{181{,}219{,}188.4}{(1+0.03)} + \frac{184{,}368{,}146.4}{(1+0.03)^2} + \frac{187{,}517{,}104.5}{(1+0.03)^3} + \frac{190{,}666{,}062.5}{(1+0.03)^4} + \frac{193{,}815{,}020.6}{(1+0.03)^5} + \sum_{t=6}^{5} \frac{80{,}775{,}020}{(1+0.03)^t} = 1{,}177{,}022{,}566$$

5.5. Costs summary

To finalize the accounting of the costs, I want to comment briefly on the dynamics of the costs and the differences between them.

It is very clear and also intuitive that Project C has the lowest costs as it does not partake in any widespread investments and just focuses on the maintenance of the current system.

What is curious, is that between Project A and B there is not as big of a difference as one might have assumed at first. This is mainly due to the fact that the extra years of maintenance and energy spent on HPS in Project B take a big toll on the budget of the project. With a STPR of 3% Project A is a few million euros cheaper than project B and the other way around on the 3.5% making Project B cheaper than A.

One last thing I would like to add to close the cost section of this study is that I will be doing a sensitivity test upon the impact that sleeping deprivation has on the analysis. This is mainly due to the fact that the estimation of this effect is not perfect and would require massive amounts of data and studying to get it to be as robust as I would like. So just to be sure I will be providing a sensitivity test at the end of the analysis in order to see the differences when this effect is taken out of the picture.

6. The Benefits

Moving on to the benefits side I will be taking a different approach in the methodology and structure of the benefit accounting. First I will be describing the benefits brought in by the incorporation of LED lights; then I will be doing the different accounting required for the different projects.

Where things take a sharp turn is in the accounting of the benefits for project C. As this project is taken to be as the baseline project; the benefits brought by it are not going to be as noticeable as for the other projects which do change the situation of the infrastructure and hence I will be omitting them.

Inarguably, one of the biggest benefits brought by LED lights is that with its better visibility and lighting capacity there are several studies that point towards reductions in crime and accidents. One can see how this can obviously have a very powerful impact upon the analysis as crime and accidents are two of the most costly and damaging phenomena that a society can have.

A study published in the Sage Journal by Brandon C. Welsh and David P. Farrington found that the implementation of LED lights decreased overall crime by 7% on average in US cities and by a whopping 38% on average in UK cities. Another study conducted by the National Bureau of Economic Research found that LED lighting had a nighttime crime index reduction of 36%. These huge differences are explained by many factors ranging from how much more violent the US is compared to European standards, to very specific country related factors were culture and city planning can make a huge difference; it is no secret that cities in the US have much less foot traffic than those in Europe. What remains clear is that crime was severely reduced in both cases even though in the US it didn't do as much as in the UK in overall terms.

As done previously I will be taking the average of these two estimates to apply it to the analysis. It can be argued that with such big differences there might be some issues when it comes to taking the average. It could very well be that to the case of this analysis where it is being based in Spain that more precise and country specific data is required. Being that this is a relatively new area of study there is not much data in Spain for these kinds of issues; hence I will be taking the 22.5% crime reduction in hopes of trying to estimate this effect as fairly as possible. This figure is closer to the one estimated in the UK and that is also a good thing. The UK and Spain are much more alike than with the US. They both have similar police models, dense urban fabric and high pedestrian activity, hence it is not a bad thing that the number is closer to that of the UK than the US.

Having said this, another question arises. How much is crime reduction worth? According to "EpData", at the end of the 4th trimester of 2025 there were a total of around 169,600 crimes reported in the city of Barcelona. This statistic counts homicides, sexual assaults, thefts, house and store break-ins, violent theft, kidnappings, and vehicle thefts. One problem that comes with analysing crime in general is the fact that not all crime costs the same. A homicide has an immeasurable cost; and even if we try to measure it through different proxies, such as the value of a statistical life, we end up seeing that it is much higher than any pickpocket or regular theft can be. This is why I will be breaking down each crime statistic into different costs brought in by it. This methodology has one flaw that is the fact that the

crime reduction brought in by LED lights is measured in general terms, and has no data for specific types of crime. Hence, I will be applying the overall crime reduction to each of the different crimes as to make calculations simpler.

For the calculation of each individual cost I will be taking data from the UK again as they have the better studies done, and the data is much more available than in Spain. For this reason I will use the values provided in this study converted to euros.

Table 1: Cost of crime in Barcelona

	Rape	Homicides	Theft	Break-ins	Violent thefts	Vehicle thefts
Barcelona 3-year average	450	11	80,722	6337	12,943	2,963
Unit cost	45,346	3,707,142	1,466	10,695	15,162	26,193
Total	20,405,700	40,778,562	118,337,963	67,770,650	196,241,766	77,609,859

Sources: Personal elaboration done with data extracted from EpData and the UK government's Home Office "The economic and social costs of crime"

One thing I would like to point out is that I am using the converted values from pounds to euros. I am choosing to use the average conversion rate of the last 10 years which is 1.15 euros for each pound. The fluctuations and differences in income may be over or underestimating the different values but due to the lack of data in Spain this will have to suffice. The total cost of crime in Barcelona for the year 2025 is around 521,144,500 euros.

I will be providing the calculations of how much do the reductions in these crimes mean for society, but first I would like to finish establishing the key benefits of the change in lighting infrastructure. In order to do this I will also be analysing what impact does the better visibility of LED lights bring to vehicle accidents.

A study published by the "Universidad de Murcia" in collaboration with the company "Sigma Dos" found out that the cost of one fatal accident in Spain is around 2 million euros. This makes sense as the value of a statistic life in Spain is calculated to be around 1.9 million

euros. Being an accident usually means less expenses in judicial system and police as there might be less or even no prosecution done as in the case of the homicide. This study also calculates the cost per wounded in an accident; for a severe case the costs go up to 385,480 euros (counting severe wounded as they spent more than 24 hours in the hospital), and for mild wounds (those that spend less than 24 hours in the hospital) the amount goes to 8,506 euros.

These numbers combined with the statistic provided by the "Ajuntament de Barcelona" we can get a rough estimation of the costs brought in by vehicle accidents in the city for a year. The data that is available for the number of accidents in Barcelona is for 2023 and 2024. I will be taking the average of the two as done previously.

Table 2: Cost of vehicle accidents in Barcelona in 2023-2024

	Traffic deaths	**Grave injuries**	**Mild injuries**
Quantity	16	235	8,398
Cost per accident	2,000,000	385,480	8,506
Total	32,000,000	90,587,800	71,433,388

Sources: Personal elaboration done with data from "La Moncloa, Universidad de Murcia and the Ajuntament de Barcelona"

Adding all the costs we have that each year the city of Barcelona looses around 194,021,188 euros due to vehicular accidents. A study published in the "National Library of Medicine" done by Fiona R. Beyer and Katharine Ker (2005) reviewed 17 different studies across the years and found out that due to better street lighting there is around a 32% reduction in total crashes; with that representing a 34% reduction in injuries and 66% reduction in fatal crashes.

These are the main benefits that I will be analysing. There are many more possible inclusions in the benefits sector (as well with the costs) but the data available is not as reliable as I would like it to be. One key issue that I want to mention is the absence of a calculation based on the reduction of CO_2 emissions. Although some benefits of this are already internalized due to the reduction in energy consumption in LED lights; the local scoping bounds that I have decided for this project make it so that by including measures such as the

"Social Cost of Carbon" or the "EU ETS carbon credit savings" would drive this analysis out of proportion and out of the local perspective that I would like to keep. These effects would increase the benefits further but in order to try to be as cautious as possible I will be omitting these, despite how important they are.

6.1. Benefit structure of Project A

I will start by the simplest case to analyse, given that it provides a good entry and understanding to the amount of benefits brought in by these projects. In this project, from the very beginning the benefits brought by LED lights are already at play and in full force. For this reason I just need to see the reductions in both crime and accidents and compute the benefits per period that these represent.

Table 3: Benefit gained from crime and accident reduction

	Rape	Homicide	Theft	Break-ins	Violent Theft	Vehicle theft	Traffic deaths	Grave injuries	Mild Injuries
Amount reduced	101,3	2,5	18.162,5	1.425,8	2.912,2	666,7	10,6	79,9	2.855,3
Benefit gained in euros	4.591.282 €	9.175.176 €	26.626.152 €	15.249.145 €	44.154.473 €	17.462.349 €	21.180.000 €	30.799.852 €	24.287.352 €
Total	193.525.781 €								

Sources: Personal elaboration with data from "EpData, the UK government's Home Office "The economic and social costs of crime", La Moncloa, Universidad de Murcia and the Ajuntament de Barcelona".

As shown in the table above, the total benefit gained per period in Project A is 193,525,781 euros. This figure is derived from the percentages of reductions in crime and accidents that studies indicate on the number of events occurred and that is multiplied by the cost per unit of each even (crime or accident). I have chosen to not round out the numbers in order to try to be as fair as possible. Given that we are dealing with statistics here and not actual cases, things like the 2 and a half homicides reduced per year may not make too much sense as there is no such thing as half a person or half a murder, but it does when it comes to a "statistical life".

With all the benefit computing done for project A, I can finally see how much this means in present terms for the viability of the project. The actual benefit accounting for this project is rather simple. As we are starting from the basis that the LED lights are installed during the

first period, and assuming that the benefits enjoyed during that period are the same as in the others in order to keep things as simple as possible. We get that:

Present Benefit of Project A:

$$Benefit\ of\ Project\ A_1: \sum_{t=1}^{10} \frac{193{,}525{,}781}{(1+0.035)^t} = 1,609,477,540$$

$$Benefit\ of\ Project\ A_2: \sum_{t=1}^{10} \frac{193{,}525{,}781}{(1+0.03)^t} = 1,650,814,166$$

These results already shed a bright new light into this project as it is plain and clear that they are bigger than the costs, but that analysis will be carried out further down the study. For now, I have to shift my focus into the benefit calculation of Project B.

6.2. Benefit structure of Project B

For project B things are not so straight forward. Due to the fact that the first 5 periods all have different amount of LED lights installed I will have to do the benefit calculation accordingly. For this I will provide one table detailing the first 4 periods of the benefits and for the second half I will use the value obtained from **table 3** as they are the same.

Table 4: Project B benefit accounting per period

		Rape	Homicide	Theft	Break-ins	Violent Theft	Vehicle theft	Traffic deaths	Grave injuries	Mild Injuries
Period 1	Amount reduced	20,3	0,5	3.632,5	285,2	582,4	133,3	2,1	16,0	571,1
	Benefit gained in euros	920.523,8 €	1.853.571,0 €	5.325.245,0 €	3.050.214,0 €	8.830.348,8 €	3.491.526,9 €	4.200.000,0 €	6.167.680,0 €	4.857.776,0 €
	Total for Period 1	38.696.885,5 €								
Period 2	Amount reduced	40,5	1,0	7.265,0	570,3	1.164,9	266,7	4,2	32,0	1.142,1
	Benefit gained in euros	1.836.513,0 €	3.707.142,0 €	10.650.490,0 €	6.099.358,5 €	17.662.213,8 €	6.985.673,1 €	8.400.000,0 €	12.335.360,0 €	9.714.702,6 €
	Total for Period 2	77.391.453,0 €								
Period 3	Amount reduced	60,8	1,5	10.897,5	855,5	1.747,3	400,0	6,3	47,9	1.713,2
	Benefit gained in euros	2.757.036,8 €	5.560.713,0 €	15.975.735,0 €	9.149.572,5 €	26.492.562,6 €	10.477.200,0 €	12.600.000,0 €	18.464.492,0 €	14.572.479,2 €
	Total for Period 3	116.049.791,1 €								
Period 4	Amount reduced	81,0	2,0	14.530,0	1.140,7	2.329,7	533,3	8,4	63,9	2.284,3
	Benefit gained in euros	3.673.026,0 €	7.414.284,0 €	21.300.980,0 €	12.199.786,5 €	35.322.911,4 €	13.968.726,9 €	16.800.000,0 €	24.632.172,0 €	19.430.255,8 €
	Total for Period 4	154.742.142,6 €								
Period 5 Onwards	Amount reduced	101,3	2,5	18.162,5	1.425,8	2.912,2	666,7	10,6	79,9	2.855,3
	Benefit gained in euros	4.591.282,0 €	9.175.176,0 €	26.626.152,0 €	15.249.145,0 €	44.154.473,0 €	17.462.349,0 €	21.180.000,0 €	30.799.852,0 €	24.287.352,0 €
	Total for Period 5 onwards	193.525.781,0 €								

Source: Personal elaboration with data from "EpData, the UK government's Home Office "The economic and social costs of crime", La Moncloa, Universidad de Murcia and the Ajuntament de Barcelona".

The progressiveness of the accounting of benefits is very similar to those done in the costs of Project B. Each period was calculated taking into account the amount of LED lights in the city at that time. As previously explained in the cost section of this project, this is not the most realistic approach but the compromise that has to be reached in order to not overcomplicate things.

Now the present value of the benefits for Project B is:

$$\frac{38{,}696{,}885.5}{(1+0.035)} + \frac{77{,}391{,}453}{(1+0.035)^2} + \frac{116{,}049{,}791.1}{(1+0.035)^3} + \frac{154{,}742{,}142.6}{(1+0.035)^4} + \sum_{t=5}^{6} \frac{193{,}525{,}781}{(1+0.035)^t} = 669{,}530{,}006.9$$

$$\frac{38{,}696{,}885.5}{(1+0.03)} + \frac{77{,}391{,}453}{(1+0.03)^2} + \frac{116{,}049{,}791.1}{(1+0.03)^3} + \frac{154{,}742{,}142.6}{(1+0.03)^4} + \sum_{t=5}^{6} \frac{193{,}525{,}781}{(1+0.03)^t} = 683{,}218{,}880.2$$

With all the calculations finished I can move onto the actual analysis and conclusion for this study. As mentioned previously, project C will not have any benefit calculations done as it is the baseline case and all the benefits that it brings are already implicitly accounted for.

7. Analysis of the viability of the projects

The following table contains the results of the projects and how many profits or losses each brings to the city.

Table 5: Net gains from realization of the projects.

Project	Costs	Benefits	Total
Project A	-1,155,916,348	1,609,477,540	453,561,192
(STPR 3%)	-1,172,956,604	1,650,814,166	477,857,562
Project B	-1,152,742,346	669,530,006.9	-483,212,339.1
(STPR 3%)	-1,177,022,566	683,218,880.2	-493,803,685.8
Project C	-427,234,247.3	0	-427,234,247.3
(STPR 3%)	-438,207,014.4	0	-438,207,014.4

Source: Personal elaboration

As it is clearly shown in table 5, Project A is the only viable project in monetary terms. It is the only one to have a positive balance and together with that it is the one which changes the

lights the fastest.

Project B sufferers from the slow gains from the benefits brought in by LED lights as it has higher costs as well due to the fact that there are periods with a lot of expenditures due to both HPS and LED lights coexisting and generating extra costs and not the extra benefits. This puts it so that even if the option for Project A was unavailable, in this specific 10-year period, one would still have to choose to do project C instead of B as it has lower overall costs.

This could change if I extended the time limit of this analysis. Given enough time, LED lights bring massive benefits to society and the further we go in time the easier it is to see this.

Still, Project A being available is the clear winner. What is interesting to take out of these results, is that the faster society implements LED technology on its streets the better everyone will be. This can give some very insightful policy implications and shifts in priority when it comes to the selection of projects by public entities.

7.1. Sensitivity analysis

In order to provide the fairest view possible, I will be conducting a sensitivity analysis on the costs of sleep deprivation and another on whether the short time constrain has compromised the analysis in any meaningful way.

Sleep deprivation sensitivity analysis

For this sensitivity analysis I will be simply redoing the calculations without the sleep deprivation costs and see whether this has a big impact on the trends seen in the analysis. Being a huge part of the cost structure I know it will have an impact on absolute values but what I am interested to see is that if it changes the overall outcome.

Table 6: Net present value of the projects without sleep deprivation costs

Projects	Costs	Benefits	Total
Project A	-627,544,485.8	1,609,477,540	981,933,054.2
(STPR 3%)	-632,192,522.1	1,650,814,166	1,018,621,644
Project B	-640,135,929,7	669,530,006.9	29,394,077.2
(STPR 3%)	-650,206,184.8	683,218,880.2	33,012,695.4
Project C	-138,502,873.8	0	-138,502,873.8
(STPR 3%)	-142,060,078.7	0	-142,060,078.7

Source: Personal elaboration.

As it is clearly visible on table 6, there is a slight change when the sleep deprivation costs are factored out. Project A is still the most viable project out of the three, but now Project B is also viable from a financial perspective. Even still the difference with Project A is massive, and the correct option would still be to choose this one, although the insight given by this sensitivity test is very useful when painting the bigger picture. The shortcomings faced by project B are still due to its late incorporation of benefits rather than any extra costs faced by sleep deprivation.

One thing that I need to clarify is that I am fully aware of the fact that sleep deprivation may be overrepresented. As previously stated, this project tries to see the "worst case scenario" and even still when factoring out this effect the overall results do not change significantly.

7.2. Extending the time constraint

For the following test I will be extending the time constraint from 10 years to 20 years. I will be doing this in order to see if the arbitrary decision of 10 years, picked to try to emulate the standard planning time horizon faced by municipalities, is creating any significant distortions.

Table 7: Extended Cost-benefit calculations.

Project	Costs	Benefits	Total
Project A	-1,648,817,714	2,750,466,449	1,101,648,735
(STPR 3%)	-1,701,038,663	2,879,174,942	1,178,136,279
Project B	-1,411,287,480	1,978,841,023	567,553,543
(STPR 3%)	-1,452,282,206	2,065,749,755	613,467,549
Project C	-730,108,643.1	0	-730,108,643.1
(STPR 3%)	-764,274,187.3	0	-764,274,187.3

Source: Personal elaboration.

By extending the time constraint, it is plain to see that the results follow the same path as the previous sensitivity test. Project A still is the one that has the biggest benefit and now Project B is viable but, still trails behind Project A.

This only reinforces the concept that the transition of HPS lights to LED, has to be rather quick. The sooner society starts enjoying the benefits from LED lights, the better.

8. Conclusion

This project has shown to be much more insightful that I may have realized at first. Street lighting is something that nowadays is taken for granted. Everyone has got used to the yellowish light that turns on at night in every city. HPS bulbs have been the staple of progress

of the 20th century and hence why for most people this might not be something that is up for debate. HPS lamps having been the standard for over 50 years makes it so that many do not see the massive burden that they can represent in so many aspects.

In an era where each day one is reminded that energy consumption and savings are vital for individuals and society as a whole; we tend to forget of the simplest changes that could be made to improve dramatically the lives of those involved.

Before starting this project I had a vague idea of the energy savings and the initiatives shown by different public administrations to adopt the LED technology into public infrastructure. What I did not realize at the time was that there were even more benefits to be had than just pure financial savings from less energy consumption. I also did not have any idea the impact that light at night may have on individuals and their health.

In my minds eye, it is extremely clear what needs to be done with the public lighting infrastructure; it is time for a change, and it has to be fast. I do have some concerns and notes that I would like to add for future investigation and consulting.

First, I would like to point out that the data for an analysis such as this is not the best there is. Not to say that the data is bad or anything, but it is kind of underwhelming how little data there is available on topics related to energy savings and the impact of better public lighting in Spain. I think these are topics worth researching as it could be that the numbers change by significant degrees when it comes to the reductions in crime or the disturbances of circadian rhythms.

Second, I believe that there needs to be more research done in the biological impact that LED lights may have on humans, animals, and insects. What I have come to realize after doing this project is that in things that have such a wide impact such as public lighting infrastructure one needs to try to analyse the possible externalities to their fullest. As it can get tricky when a project generates unforeseen externalities and ends up affecting crucial areas as can be the wildlife and ecosystem of a city.

Overall, taking into account this concerns, I do feel that I can say that my initial hypothesis that the transition should be done faster rather than later has been proven correct. The issues pointed out above only motivate me to maybe revisit this analysis in a few years and see how things have changed and if there are better alternatives in the future. The efficient management of energy is already one of the most important areas of study and planning for all economies. With things like AI data centres and the increase in consumer demand for electricity, it is plain to see how critical any improvement in the management of energy can and will be. If this analysis has shown anything, It's that the pace of the transition matters as

much as the transition itself.

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