Innovative Lighting Systems: Opportunities for Energy Savings

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Abstract

This paper analyses, from an energy flow perspective, the implementation of smart lighting systems in street lighting, where lights are dimmed to adapt to the flow of objects passing in a street. The research focus on the sustainability perspective of implementing a transition to smart lighting systems when compared to regular LED lighting. To account for externalities, the energy flow was addressed considering the extra electronic devices used in a smart lighting system (controllers, motion sensors, radars, and computers).

To compare both traditional LED street lighting and smart lighting the paper started with a model of a 2.5-kilometre street, scaling up scenarios of the commune Ecublens, in the Swiss canton of Vaud, and then to half and all residential streets of Switzerland were examined to understand if the gains in energy savings are scalable.

The research shows that, even with the additional electronic devices, the smart lighting system reduces the energy consumption of street lighting, even when considering the production of the extra components used. Financially, the extra costs of implementing smart lighting systems are offset by the savings in electricity consumption. Therefore, smart lighting systems for street lighting can be an environmentally and economically beneficial project to implement.

Keywords: smart lighting, street lighting, sustainability, energy flow, energy savings

1. Introduction

In the light of the United Nations Sustainable Development goals, it is not only needed to combine efforts of public policies, corporations, and civil society but also actions from the public sphere to minimize waste and optimize processes, where public entities play not only the role of regulating and monitoring. Boons (2009) affirms that sustainable development requires system changes in both production and consumption.

The development and success of those goals depends on innovation rather than continuing the activities like usual. The Oxford Dictionary defines innovation as "A new method, idea or product", where usually when relating to tackling global or societal challenges, the expression of social innovation, which Stanford defines as: "A novel solution to a social problem that is more effective, efficient, sustainable, or just than current solutions. The value created accrues primarily to society rather than to private individuals", is used. Clean technology innovations address global problems, generating similar or better outcomes.

Hart and Milstein (1999) called sustainability a new factor that fosters creative destruction, generating an unprecedented opportunity, this idea brings into light sustainability as the innovation, the development of new products, services and as consequence, companies.

Bebbington et al. (2007) says that there is a widely recognized need for assessing the degree in which current activities are unsustainable, turning off the lights is the most common answer to energy savings actions one could take (Lundberg et al., 2019), yet public lights on the streets are continuously on, regardless of its usage. This paper analyses, from an energy flow perspective, the implications of using smart lighting systems for public illumination, and it gives the pathway for development, scaling up, and an assessment of this cleantech innovation value.

Schreuer (2017) shows the case of Belgium, the country with the world's highest light pollution, where it leaves street lighting on all night on roads, allegedly for security reasons, but the article shows that it might be due to lobby and internal policies/governance of the country. In this regard, smart lighting could be a useful tool for Belgium to reduce energy pollution, and electrical consumption, while leaving luminaires on, for the same

allegedly security reasons.

There's an economic pressure on cities to minimize costs and being more efficient with resources. The impact of economic policies can be studied with material and energy flow models (Binder, 2007). Street lighting is an essential factor in public energy expenditure, therefore, it's crucial to implement street lighting systems that avoid energy waste and pollution (Beccali et al., 2019).

According to the National Electrical Manufacturers Association of the USA (NEMA, 2015), the LED technology, has a linear increase of energy per light emitted, when dimming, 100% of lumens have 100% of input power, while 20% of lumens have 20% of input power. This shows, that dimming the streetlights when there's no flow of people, could be useful to reduce the energy consumption of cities and maintain the sense of security levels from street lighting (since it's dimmed, not on and off). There are systems which regulate the amount of light needed according to traffic or movement, which, when implemented in a systemic way are defined as "smart lighting". To quantify all energy flows of the processes an energy flow analysis was performed to identify possibilities to minimize the environmental impact of street lighting.

1.1 Smart Lighting Systems: CityZen

This research project analyses CityZen smart lighting offer from an energy flow perspective, to understand how the technology can be scaled and if it is more sustainable than not-connected LED street lighting systems. For CityZen, a project using Schreders products by BG consulting, smart lighting is the regulation of street lighting to the amount needed.

There are three products for smart lighting in the Schreder portfolio:

a.   Stand-alone: One motion sensor per light, the light intensity increases, or it is initiated when there is a movement close to it.

b.   Autonomous network: Can have one or multiple motion sensors or radars, the lighting poles are connected through WiFi signal, and a signal is passed to change the light intensity for multiple poles. It can act in accordance with the time of the day (e.g., at 18h00 during winter street light must be at 100%, even if traffic is lower than average, due to security or regulation) and to the flow (e.g., one car will increase the luminosity in 20%, two in 22%). It's necessary in-situ management for changing system regulations.

c.   Interoperable network: It works the same way as the autonomous network with the only difference that a fixed lighting intensity can be set during certain hours. Each 150 lighting poles are connected to a server, which sends the data to an off-site computer. This system allows to be managed from apart, also any problem in the network is pointed in the computer and the maintenance can be done for the specific part on a given place.

This paper will focus on the interoperable network, a system that Schreder defined as the most innovative, which minimizes maintenance costs and timing (since possible problems are managed on the computer) and generate data to better optimize the system. There will also be a comparison of the same system but using LED lighting without the dimming (constant light emitted all night) to understand the energy impact (positive or negative) from the technology.

This smart lighting system uses the Ampera Schreder luminaire, which according to Schreder (2015) has a LED lifetime (when exposed to a temperature of 25oC) of 100.000 hours, considering that there's 4359 hours of night-time per year in Ecublens (VD-CH), the lifetime of the light under this condition is almost 23 years. Considering all digital systems in the interoperable network, it's possible to assume that the lifetime of the luminaire is higher than other hardwares and softwares in the system, considering past technological advancement in the 23 years' timeframe, there'll be multiple software and hardware (computer, server, data centre) updates and necessary changes.

When considering the costs of implementation for smart street LED lighting, the Los Angeles (USA) implementation by Philips costed the city USD 57 million for 172.000 lights (Maddox, 2016), totalling around USD 331,40, per light (considering the other system parts inside the cost of each lamp, e.g., servers). Another provider of smart grid systems, Silver Springs (2013), charge USD 572 per light (USD 399 for the LED lamp, USD 49 for the network costs and USD 123 for software), for a city model with 50.000 lights, giving a ROI of 6 years due to energy savings. Taking into consideration that cost savings is the major driver for energy efficiency projects (De Groot et al., 2001).

This study considers a small testing scenario of a 2,5km street in Ecublens, the whole district of Ecublens and a Switzerland's scaling up for half of all luminaires in residential streets and for all luminaires in residential street, being 10, 1050, 103 700, 207 400 respectively for the number of luminaires.

2. Results

2.1 Smart Lighting System: Opportunities for Energy Savings

Considering, that street lighting systems in Switzerland have energy input only during night-time, it's necessary to understand the night hours in the examined region. There is on average 4359 hours of night per year in Ecublens, but this distribution changes along the year since there are longer nights during winter than summer.

The Figure 1, which illustrates the average night-time per month, shows that during summer there are less night hours per month (around 38% of the time is night-time). The energy consumption is consequently not only dependent on the variable of passing items, but rather also on the season and its corresponding month.
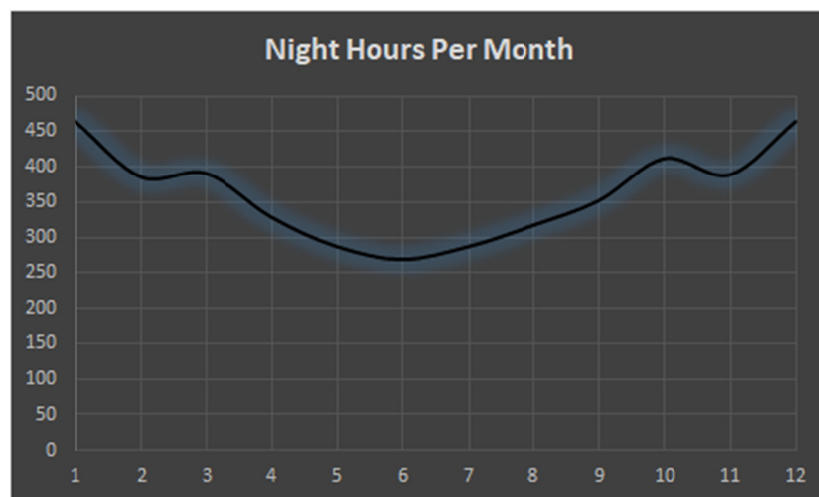

Figure 1. Hours of night per month (produced by the authors, 2017)

Since the interoperable network can be adjusted to have a fixed settings mode (continuous mode), within the model the fixed settings mode is during a period with high fluctuation in movement of items. This period is when people are usually commuting. Consequently, the fixed settings mode is from 6am–9am and 4pm–9pm, shown on Table 2. The characteristics of the two different modes are displayed in Table 1.

Table 1. Operating modes of the interoperable network (produced by the authors, 2017)

Operating mode	Autonomous mode	Fixed Settings mode
Minimum intensity	40%	80%
Maximal Intensity	100%	80%
Intensity by time	Fluctuating intensity	Constant intensity
Influence of items	Influence by detected items	No influence by detected items

Based on the night hours, the number of hours operating in the autonomous and in the fixed settings were calculated (Annexes) per season, as it is possible to see on Figure 2. With summertime having the least fixed settings usage due to longer day light periods.

Table 2. Composition for autonomous and fixed settings modes (produced by the authors, 2017)

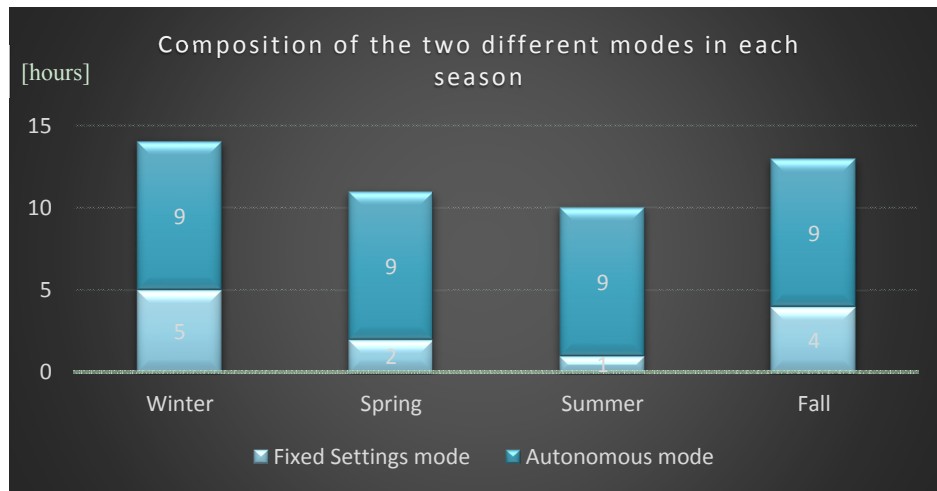| Season	*Mean* of night hours per day	Autonomous mode (fixed despite season)	Fixed settings mode = night hours – autonomous mode
Winter	14.47 ≈ 14	9 hours	5 hours
Spring	10.87 ≈ 11	9 hours	2 hours
Summer	9.56 ≈ 10	9 hours	1 hour
Fall	12.68 ≈ 13	9 hours	4 hours

Figure 2. Showing the composition of the two different modes in each season (produced by the authors, 2017)

Based on the night hours, the number of hours operating in the autonomous and in the fixed settings mode could be calculated. The autonomous mode unchanges, regardless of the season. The reason for that is, that it was used the autonomous mode only during the 'main sleeping hours' which doesn't varies much from season to season.

The average nightly volume of items passing in residential streets is important, when determining the energy consumption of the autonomous mode. Figure 3 illustrates how the energy consumption of the radar develops in dependency of the quantity of items passing.
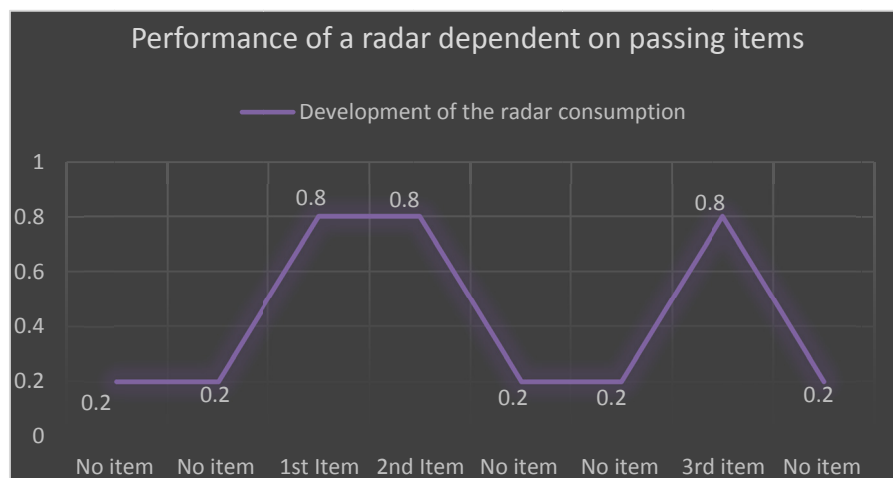

Figure 3. Illustrates the development of the performance dependent on the variable item (produced by the authors, 2017)

It runs with a constant value if no item is detected. If an item is detected, the performance increases by a distinct value. The radar has hence two different values for the energy performance. The same goes for the luminaire, with the LED energy performance increasing linearly to lumens emitted.

When an item is detected by the radar or motion sensor, they communicate with a luminaire making them aware that they should prepare to increase the intensity of light. Therefore, one can identify that the communication between motion sensor or radar and the luminaire can be considered as a chain of cause and effect. There are two different scenarios, which can occur; The first scenario Figure 4 is when no item is detected. In this case the luminaire remains constant at its low intensity level. Figure 5 shows the second scenario, in which an item is detected, and the luminaire is afterwards increasing its intensity to almost one hundred per cent in a linear way.
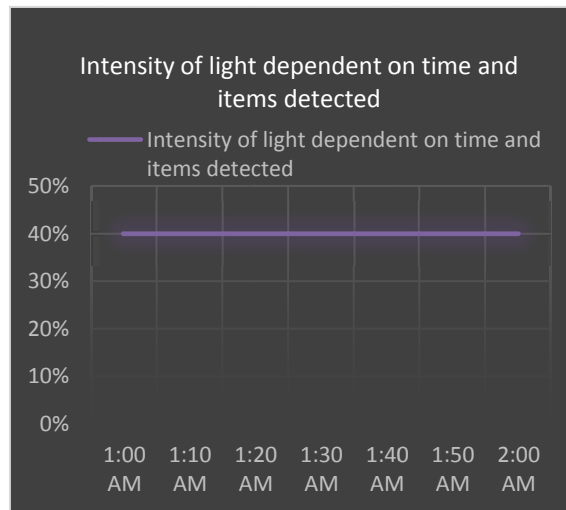
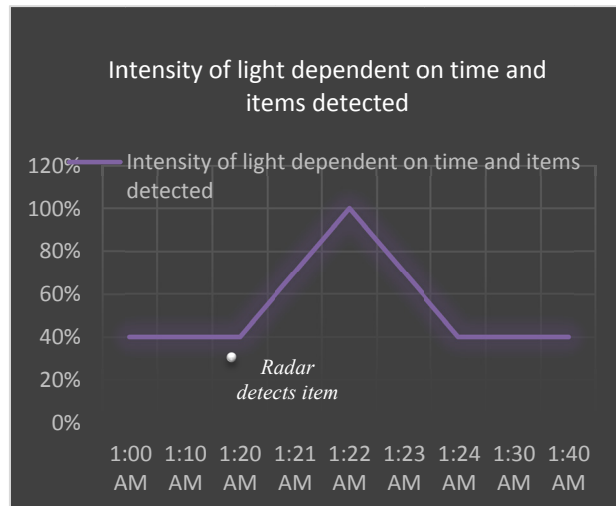Figure 4. Development of light intensity (produced by the authors, 2017)

Figure 5. Light intensity in case of detected item (produced by the authors, 2017)

Since LED energy consumption is linear, it's possible to observe a similar pattern on the energy consumption of the system in the autonomous mode.

When an item was detected, the light intensity increases linear to 100% and decreases linear back to 40% of light intensity. The cycle of in- and decrease lasts for three seconds and that the items are passing at different moments in each hour to simplify the model. Figure 6a illustrates the in- and decrease of light intensity. Figure 6b shows the simplified model to calculate the energy consumption of one single intensity, using the luminaire performance data (eq. 1).
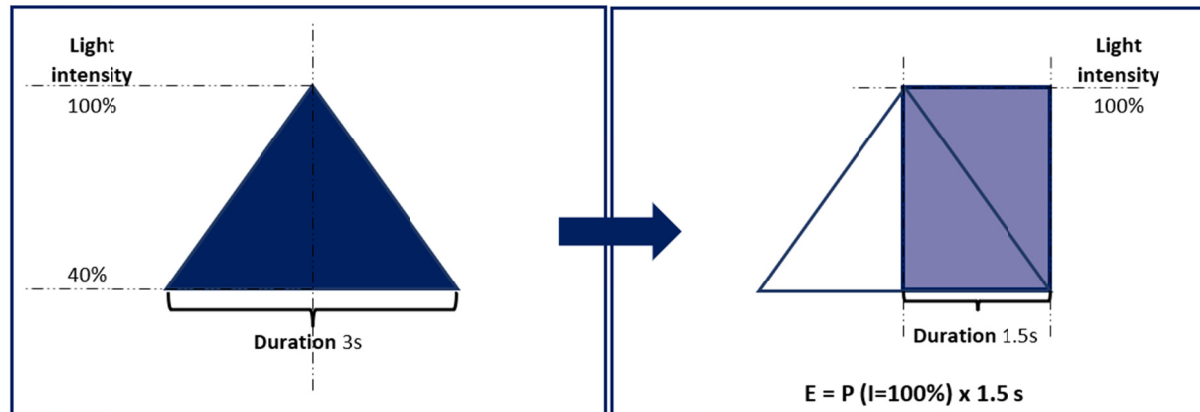
Figure 6. Showing the development of the intensity (a) and simplifying calculation of the intensity (b) (Produced by the authors, 2017)

The used luminaire 'Ampera Midi' has a range of performance between 45 W and 150 W The performance in W per intensity (%) is seen in equations 1.

$$P(I) = \begin{cases} P=0W & , I=0\% \\ P=60W & , I=10\% \\ P=70W & , I=20\% \\ P=80W & , I=30\% \\ P=90W & , I=40\% \\ P=100W & , I=50\% \\ P=110W & , I=60\% \\ P=120W & , I=70\% \\ P=130W & , I=80\% \\ P=140W & , I=90\% \\ P=150W & , I=100\% \end{cases}$$

$$(1)$$

I_i = Intensity in per cent [%]

MinP = Minimal available performance [W]

MaxP = Maximal available performance [W]

Using this data, together with the numbers of items passing and night hours per season, it was possible to determine the energy consumption of the smart lighting per year. As for the steady state LED lighting system, it was considered steady state of energy input during all night-time. In case of the smart system the energy consumption of the additional electronical devices was considered.

The energy consumption of the four scenarios is illustrated in Tables 3 and 4 for the conventional and smart lighting system respectively. Figure 7 gives a comparison of the energy consumption for each system.

Table 3. Energy consumption [kJ/y] of each process in different scaling up scenarios of the conventional lighting system (produced by the authors, 2017)

System	Conventional lighting system - Energy Consumption			
	1st scenario	*2nd scenario* *The commune of Ecublens*	*3rd scenario* *Half of all residential streets in Switzerland*	*4th scenario* *All residential streets of Switzerland*
Luminaires	18 921 600	1 968 768 000	196 216 992 000	392 433 984 000
Radars	-	-	-	-
Controllers	-	-	-	-
Segment controllers	-	-	-	-
Internal server	-	-	-	-
Computers	-	-	-	-
Total energy consumption	**18 921 600**	**1 968 768 000**	**196 216 992 000**	**392 433 984 000**

Table 4. Energy consumption [kJ/y] of each process in different scaling up scenarios of the smart lighting system (Produced by the authors, 2017)

System	Smart lighting system – Energy Consumption			
	1st scenario	*2nd scenario* *The commune of Ecublens*	*3rd scenario* *Half of all residential streets in Switzerland*	*4th scenario* *All residential streets in Switzerland*
Luminaires	15 424 061	1 619 526 353	159 947 507 400	319 895 014 800
Radars	19 205	2 016 571	199 160 413	398 320 826
Controllers	236 520	24 834 600	2 452 712 400	4 905 424 800
Segment controllers	23 652	165 564	16 351 416	32 702 832
Internal server	473 040	496 692	49 054 248	98 108 496
Computers	21 310	22 378,73	2 216 560	4 411 810
Total energy consumption	**16 197 788**	**1 647 042 159**	**162 667 002 400**	**325 333 983 600**

The energy input from the process 'distribution grid' to the processes of the luminaires was compared, as both systems are steady-state systems, the imports equal the exports. Therefore, it doesn't matter whether the imports or exports are compared to each other. The imports of the conventional system are 18,921.60 megajoules per year, whereas the imports of the smart lighting system are 16,183.03 megajoule per year. The comparison of these two figures or flows already indicates a difference in energy supply of approximately 2,738.57 megajoules per year for a street with two intersections. The implementation of the smart system in the second scenario of whole Ecublens goes along with a decrease of about 321,725.84 megajoules in energy supply per year. The impact of an implementation of the smart light system in these four scenarios based on the assumptions done indicates, that an increase of efficiency in energy use could be achieved.

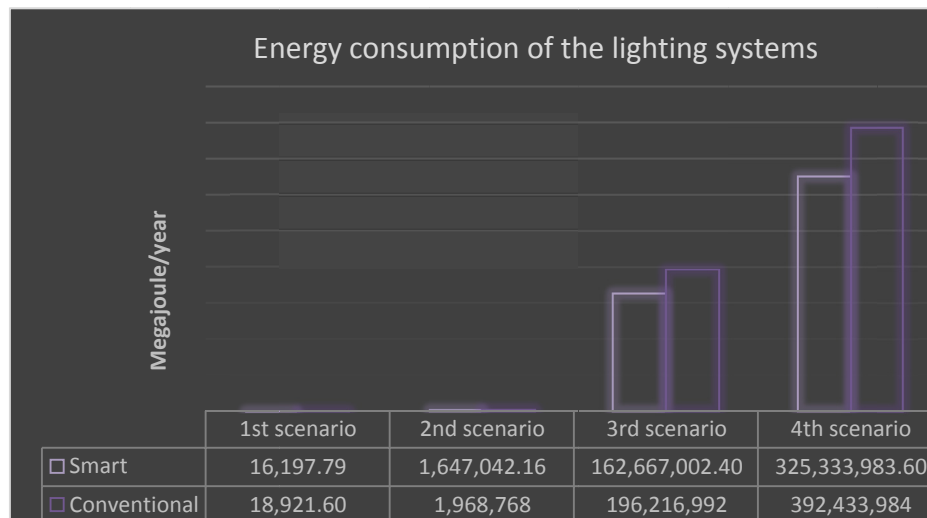*2.2 Impact on Emissions and the Corresponding High Investments*

Figure 7. Energy consumption [MJ] in different scaling up scenarios of the smart lighting system (Produced by the authors, 2017)

Figure 7 shows that the smart lighting system has an overall reduction of energy consumption, this energy reduction can be translated into return on investment when changing street lighting systems. Considering global challenges, the EU directive (European Commission, 2013) to LED for street lighting and countries tendency to reduce energy consumption, the change towards LED lights becomes inevitable.

When stakeholders need to decide between a smart or non-smart LED system, considering the 30% premium on the cost of smart, the ROI considers the break-even date achieved, while profit is over the luminaire lifetime. As is possible to see from Table 5, the profit over lifetime increases with the addition of new luminaires.

Table 5. Energy Savings and Financials, comparing smart and regular LED lighting (Produced by the authors, 2017)

Scenario	Number of Luminaires	Energy Savings per year (kWh)	ROI (Month/Year)	Profit over lifetime (CHF)
10 luminaires	10	756,61	M03Y15	883,36
Whole Ecublens	1 050	89 368,29	M07Y13	126 898,41
Half of CH residential streets	103 700	9 319 441,56	M10Y12	14 229 934,50
All CH residential streets	207 400	18 638 889,00	M10Y12	28 459 889,27

The profit per luminaire can be translated into the equation: $y = 4.8967\ln(x) + 80.449$, where y is the profit per luminaire and x the number of luminaires, the R^2 for the equation is 0,961. This profit means 6.63% return on investment for the whole Switzerland, or 5.83% for Ecublens over the investment on steady-state LED system for the lifetime.

This energy reduction is not only translated into financial return over the street lighting infrastructure, but also reduces CO2eq emissions, Table 6 shows the CO2eq reduction (when comparing smart and regular LED systems) per year. The CO2eq reduction per year can be translated into the following equation $y = 2.9661x - 77.038$, where x is the number of luminaires, with an R^2 of 1, when considering the carbon equivalent for the Switzerland produced energy, a greater reduction is seen for energy imported, representing for all residential streets in Switzerland a global reduction in carbon footprint of 0.002%, when considering the carbon emissions for 2014 (World Bank, 2014).

Table 6. C02eq in two scenarios, comparing smart and regular LED lighting (Produced by the authors, 2017)

Scenario	Number of Luminaires	CO2 eq Reduction (kg/year) CH	CO2 eq Reduction (kg/year) Imports
10 luminaires	10	24.97	97.60
Whole Ecublens	1 050	2 949.15	11 528.51
Half of CH residential streets	103 700	307 541.57	1 202 207.96
All CH residential streets	207 400	615 083.34	2 404 416.68

2.3 Sensitivity Analysis on Variable 'ItemPass'

These results are based on a consistent number of passing items during the autonomous mode of the smart lighting system. Since the number of passing items has an essential impact on the energy consumption of the radar and the luminaire, Table 7 shows the results of a sensitivity analysis of the variable 'ItemPass' on the total energy consumption (TEC) in four different scenarios. An increase of passing items goes along with a higher energy consumption due to a longer duration at an intensity of 100%, which requires the full performance of the luminaire. The scenarios 1, 2, and 3 shows that the energy savings change marginally. The fourth scenario, which illustrates an increase of 100% of the variable 'ItemPass', leads to a decrease of almost 5.98% in energy savings. An increase of 100% is equal to one item passing every 2.5 minutes.

The results of the four scenarios examined strengthen the hypothesis, that a long-term study and a detailed simulation such as a Monte Carlo Simulation is necessary to develop for each residential district an appropriate model. Adapting the model of a 2.5 kilometres street with two intersections for each residential street of Ecublens or whole Switzerland is not detailed enough to meet the local circumstances and needs, which vary from location to location.

Table 7. Sensitivity analysis for passing items and energy consumption kJ/year (Produced by the authors, 2017)

	Model +/- 0%	1st scenario +10%	2nd scenario +25%	3rd scenario +40%	4th Scenario +100%
Total Energy Consumption **Conventional Lighting Model**	18 921 600	18 921 600	18 921 600	18 921 600	18 921 600
Constant Energy consumption (No influence by variable 'Passitem')	754 522	754 522	754 522	754 522	754 522
Radar	19,205	19,233.8	19,276.4	19,318.96	19,489.25
Luminaire	15,409,278	15,412,818.5	15,419,561.9	15,423,476.5	15,444,756
Total Energy Consumption	**15,428,483**	**15,432,052.3**	**15,438,838.3**	**15,442,795.5**	**16,218,767.25**
Δ to Conventional	**-22.64%**	**-22.61%**	**-22.56%**	**-22.53%**	**-16.66%**

2.4 Energy Flow Along the Value Chain

The energy savings identified for the four scenarios goes along with an additional use of electronical devices. These electronical devices require a huge amount of energy during their production. From an environmental point of view, the additionally emerging energy consumption during their production must be considered, if it comes to an overall assessment of the energy use along the value chain. Zundritsch and Hewes (2017) calculated the additional energy consumption during the production. Table 8 shows the impact of the additional energy consumption on the energy savings in megajoule and per cent per year. The 1st scenario ensures still energy savings of approximately 2 732.81 megajoules per year or 16.82 %. Whereas the 4th scenario points out 67 100 000.40 megajoules saved per year or 20.29%.

Table 8. Energy Consumption during production of the additionally used electronical devices included (Zundritsch & Hewes, 2017)

	1st scenario	4th scenario
	Model of 2.5 kilometers	All residential streets of Switzerland
Total Energy Consumption **Smart**	16 197.79 MJ/y	325 333 983.60 MJ/y
Additional energy consumption of electronical devices (during production broke down per year)	397.72 MJ/y	916 527.76 MJ/y
Total Energy Consumption **Smart including additional energy consumption**	16 595.51 MJ/y	326 250 511.40 MJ/y
Total Energy Consumption **conventional**	18 921.60 MJ/y	392 433 984.00 MJ/y
Δ **Total Energy Consumption** Conventional – Smart including additional energy consumption	- 2 723.81 MJ/y	- 67 100 000.40 MJ/y
Δ **in** %	- 16.82%	-20.29%

For instance, these two scenarios including the energy consumption occurring during the production of the additionally used electronical devices shows, that the integral assessment according to the energy flow leads in case of switching from a conventional lighting to a smart lighting system still to energy savings.

3. Methods

To better understand the lighting consumption, the variation in sunlight during the year was analysed. Since the distribution grid only sends the electrical signal when it's dark, it is relevant to understand the hours of night-time during the year, to better assess the electricity input.

To calculate the yearly and monthly sunlight time (to calculate the night-time), firstly the latitude for the region of Ecublens 46.5296^o was identified. Afterwards the solar hour, the theta (which is a ratio of pi, the day per hour divided by the number of days in a year), the solar declination (the angle in radians which represents the solar angle towards the earth) was calculated. Based on these results it was possible to define the cosZ (which is a function of the latitude, solar declination and solar hour) and the arcossin of cosZ. In case of the arcossin of cosZ is higher than 90°, it is night and if it is lower, sunlight is available. The data computed shows the sunlight angle per hour for each day of the year to be able to calculate the days and months of the Julian calendar.

3.1 System Model

The unique characteristic of cleantech innovations such as the smart lighting system exists in providing light on demand. Both energy flow analysis models don't contain any type of energy storage processes and are therefore not dependent on time. These circumstances imply constant flows and stocks:

$$M_{Stock}(0) = M_{Stock}(t), \ \frac{dM_{Stock}}{dt} = 0 \tag{2}$$

The first step in the definition of the system boundaries was identifying the different types of districts; residential, commercial, industrial, pedestrian, and school districts. Due to cities heterogenous characteristics the model must be broke down to a smaller scale, which represents only one type of district to be very close to reality. According to Schreder's data, smart public lighting systems are most useful when implemented in residential or industrial districts. An exact example of the desired neighbourhood is outlined in red and can be seen in the Quartier du Croset. Based on this residential street with help of GIS and Google Maps to calculate the average spacing between the streetlamps to get the number of streetlights used. Figure 8 and table 9 shows the important parameters determining the systems characteristics.

Table 9. Explanatory Street taken in Ecublens, VD and the Spatial System Boundary Definition (produced by the authors, 2017)

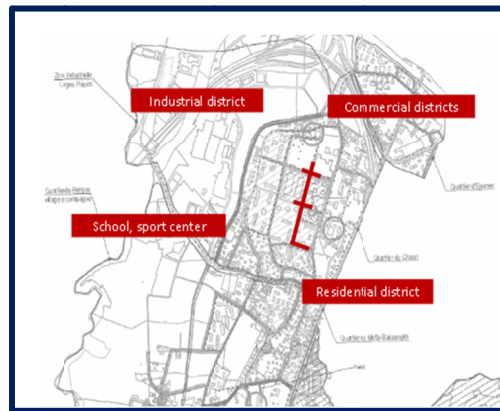| Parameter	Value
City district	Residential
Number of intersections	2
Total street length	2.5 km
Spacing of street lights	25 m
Number of street lights	10

Figure 8. Explanatory Street taken in Ecublens, VD and the Spatial System Boundary Definition (produced by the authors, 2017)

The model developed includes all relevant processes, which are affected by changing the lighting system within a city. Hence, externalities such as the additional occurring energy consumption due to the use of internet is not considered. The energy input to the luminaires and electronical devices comes from the distribution grid, which sends an energy flow only during night-time (the distribution grids in Switzerland have a solar light sensor and a timer, to regulate the energy input to street lighting systems only during the night, reinforcing the importance of calculating the day/night-time in the region).

This project used qualitative and semi quantitative methods to analyse the energy flows of the conventional and the smart lighting systems. A semi-structured interview with a representative of Schreder to discuss the different available lighting systems was followed by data collection for the structure of an energy flow model using the Stan software. Based on a deep analysis on how the two systems operate, the processes and flows could be identified and calculated for a model with a 2,5km long residential street with two intersections. Thereupon the savings in energy and emissions could be analysed in different scenarios in case of switching from a conventional lighting model to a smart lighting model. Examining the crucial influence factor of passing items with the help of a sensitivity analysis facilitated to scrutinize the assumptions and calculations made. Further, the study on the Return on Investments of the smart lighting system was performed.

3.2 Semi-Structured Interview

To understand better the different smart lighting systems, an interview with a representative from Schreder's team in Carrouge (Switzerland) was performed. The primary goal of this interview was to understand what smart lighting for street usage is and which products Schreder has on its portfolio regarding this technology. Further, what the main applications of the different lighting systems including the conventional lighting systems are. There are three smart lighting products on Schreder's portfolio:

a)   Stand alone

b)   Autonomous network

c)   Interoperable network

This research focuses on the interoperable network as the most innovative one of Schreder's portfolio combining features of the 'Stand alone' product and the 'Autonomous Network' product. The main purpose of the interoperable network is to offer a solution as a combination of autonomous and adjusted functions. It offers a light management system, which facilitates adjusting the mode and its settings. The light management system enables managing the operation and maintenance of streetlights more easily, which represents an advantage in reducing the maintenance costs of street lighting.

The smart lighting system of Schreder offers a broad range of luminaires per category, which differ in design and intensity. The most common luminaire used in residential districts is the Ampera, which attracts customers with its high efficiency and short payback period [Monet, Schreder].

There are three types of the Ampera; Mini, Midi, Maxi. The 'Mini' is primarily used on residential streets with an energy consumption between 10 and 76 W. The 'Midi' is used for commercial streets and streets with a mix of commercial and residential demand. The energy consumption in this case varies between 36 and 201 W. The third type of the Ampera product line is the 'Maxi', which is used for boulevards and highways with a

consumption between 86 and 279 W. In our case, the Ampera Midi is used to meet the demands of a residential district including commercial businesses for households needs. Moreover, using the middle-class product Ampera 'Midi' allows us to meet the demands of a commercial street as well as the demands of a residential district. And consequently, enables an analysis of different scenarios of Scaling up more realistic.

3.3 Primary Data Collection

Besides the semi-structured interview, another source of primary data collection was counting passing items at a residential street at two different days between 10pm and 11pm (Table 10) to have a more realistic number of passing items during the autonomous mode, which is operating during the deep 'sleeping hours'. In our model, the number 12 was taken for a more conservative calculation.

Table 10. Average counted items (Produced by the authors, 2017)

Measurement time	1st: Counted items	2nd: Counted items
09.00 PM – 10.00 PM	12	11

Another primary source of data was the analysis on solar hours in Ecublens (explained in chapter 2).

3.4 Secondary Data Collection

To bring the energy flow model as close as possible to the real consumption data, the consumption of the processes was calculated according to developed equations, which model the energy consumption dependent on its influences:

a)   Energy consumption of the smart lighting system processes: LED luminaire, radar, controller, internal server and computer Energy Consumption of the conventional lighting system: LED luminaire

b)   Financial: the costs of the smart lighting system divided per luminaire (the data was gathered from Philips and Silver Springs, both providers of smart lighting systems. The product costs CHF 331.40 (Maddox, 2016), respectively CHF 572.00 (Silver Springs 2013) for the one from Silver Springs. The average price was used). For all the calculations the most expensive model for the calculation was taken. Also, energy scope provided the pricing for the regular LED lighting system, for the same luminaire, with this data was possible to calculate the price difference between the regular and smart system and infer the same pricing difference for Philips.

c)   Data from the energy price in Vaud (Switzerland) per kWh for industries, with high energy usage.

d)   CO2eq: The carbon equivalent emission per kWh of energy produced in Switzerland

3.5 Calculation of Flows in the Smart Lighting System

Breaking the energy consumption down to each process of the smart lighting system, there is:

a)   The radar: Its consumption is not a constant value. It is rather dependent on the passing items (people, vehicles, animals, etc.). With every passing item, the radars consumption increases. Function of the process: detecting a moving item to communicate the detection to the luminaire to prepare for an increase in intensity

b)   The motion sensor is already included in some of the luminaires and have the same function as the radar but are not so precise. The energy consumption of the motion sensors is so low, that it can be neglected.

c)   LED luminaire: The energy consumption is constant or linear depending on its adjusted mode

d)   Controller (LuCo): The energy consumption of the controller, which is situated on every luminaire, communicates with the controllers of the other luminaires and the radars. It is running throughout the year to send requested data for the light management.

e)   Segment Controller is required for every 150 luminaires to have more preciseness in communication.

f)   Computer: the computer/tablet serves to monitor the system, intervene (by adjusting the settings for example), to check for maintenance problems, or to see data (e.g., energy consumption)

g)   Internal Server: The internal server compiles and processes the data between the controllers

Starting at the starting point of the chain of cause and effect leads to firstly computing the consumption of the radars and motion sensors. Considering, that the radars energy consumption changes with passing items, its consumption was calculated according to the equation 3.

$$ECR_y = n \times 365 \, days$$

$$\times \, 9hours \left(DetecEnergy \times \frac{ItemPass \times 1{,}5s \times 1h}{3600s} + ConstantEnergy \right) \tag{3}$$

ECR_y = Energy consumption of the radars per year

n = Number of radars used

DetecEnergy = Additional energy consumption because of detected item

ConstantEnergy= Constant energy consumption despite item detected or not

On the other hand, the installed motion sensors are integrated in some of the luminaires. The motion sensors energy consumption is not dependent on the quantity of items detected, but rather a constant value and is in our case neglectable because of its very low energy consumption.

The system operates in two modes. The fixed settings mode is during the 'Rush hours' between 4pm-10pm and 6am-9am. Whereas the autonomous mode is working during the 'deep sleeping hours' between 10pm and 6pm. The night hours are calculated as a mean for each of the four seasons according to the equation 4 to have a representative day for each season.

$$n_j = \sum_{i=1}^{3} \frac{m_t}{d_i} \tag{4}$$

nj = the mean of night hours per day for seasonj

mt = total night hours in monthi

di = days in monthi

Based on the average night-time, and considering the main sleeping hours, it was possible to develop a model for the light intensity dependent on the passing items by time for each season. The used luminaire 'Ampera Midi' has a range of performance between 45 W and 150 W.

First, a function of the performance dependent on the light intensity was needed. This can be done through scaling of the performance range. The equation to calculate the performance dependent on the intensity is seen on equation 5.

$$P_i = MinP + MaxP \times \frac{I}{100} \tag{5}$$

$$I = \{10,20,30,40,50,60,70,80,90\}$$

The next step was computing the duration at each intensity. Two different scenarios must be distinguished. The formula for each luminaire is seen at equation 6.

$$t_{\approx I=100\%} = ItemsPassing \times \frac{1{,}5s}{item \, passing} \times \frac{1h}{3600s} \tag{6}$$

$$t_{I=40\%} = 1hour - t_{\approx I=100\%}$$

t≈I=100% = Duration of passing items at light intensity ≈100% [h]

tI=40% = Duration at light intensity 40% [h]

The value for the autonomous working time is $t_{\approx I=100\%}$ in seconds per hour. The dimming settings are adjusted at an intensity level of 40%. The fixed settings mode is working with an adjusted intensity, which is constant. The recommended fixed settings by Schreder is at a light intensity of approximately 70%.

After computing the unknown variables, the energy consumption for the four representative nights for each season can be calculated according the equation 7.

$$EC_{dj} = h_a \times (t_{I=40\%} \times P_{I=40\%} + t_{\approx I=100\%} \times P_{I=100\%}) + h_f \times P_{I=70\%} \tag{7}$$

ha = hours in autonomous mode

hf = hours in fixed settings mode

ECd,j = Energy consumption per day in season j per luminaire

Finally, the final consumption per year of each luminaire could be calculated:

$$ECL_y = \sum_{j=1}^{3} \frac{365}{4} \times EC_{d,j} \tag{8}$$

ECL_y = Energy consumption throughout the whole year per luminaire [W/year]

$EC_{d,j}$ = Energy consumption per night in season$_j$ per luminaire [W/day, lum]

The value of 'ECL_y' is equal to the value of the flow 'Energy Supply' to each luminaire.

The transmission and heat losses are also known as dissipation losses. Those losses are described as an additional energy consumption, which is used by the luminaire to provide light. The amount of energy wasted is calculated as the percentage of the energy demand of each LED luminaire. Calculated according to the equation 9.

$$Losses = ECL_y \times \frac{32,5\%}{100} \tag{9}$$

The street lighting LED losses of energy is around 30 and 35 percent (Ette et al., 2009). The arithmetical mean between 30 and 35 percent was used to calculate the emitted losses by the luminaire; 32.5%. The value of the losses is equal to the flows 'Energy Losses' leaving the process of a luminaire. By setting up the equations, the value of the flow 'Energy emitted' leaving the process of the luminaire, was calculated.

The controller used in this system is the LUCO NXP, which controls the LED driver and the ballasts. It is the main process, which is responsible for the communication between the luminaires, sensors and radars in the autonomous mode. The performance of the controller varies between 0,7W and 0,8W. The controller is working throughout the year with a constant value of energy consumption. For this model, the mean of 0,75W was used.

The equation 10 shows the calculation of the energy consumption for the controller.

$$ECC_y = 0,75W \times 24 \times 365 \tag{10}$$

ECC_y = Energy consumption of controller per year [Wh]

The system is in steady-state and works even when LED lights are off (constantly receiving input to remain or change the state). Consequently, the input flows must be equal to the output flows. Therefore, the value of ECC_y is equal to the flows 'Energy Supply' and 'Energy emitted'.

The segment controller has the same function as the controller described before. It contributes to more preciseness in communication between the electronical devices. This segment controller is used for every 150 luminaires. In case of having 151 luminaires two segments controller are required. The energy consumption for each segment controller is the same of the LUCO NXP:

$$ECSC_y = ECC_y = 0.75W \times \frac{1h}{3600s} \times 24 \times 365 \tag{11}$$

$ECSC_y$ = Energy Consumption of a segment controller per year [Wh]

The in- and output flow 'Energy Supply' and 'Energy Emitted' of the controller are equal to the value of '$ECSC_y$'.

As for the data storage and management between controllers there is a server, whose energy consumption is dependent on the amount of data generated by the controllers. The server's main purpose is to provide the lighting management system, which offers adjusting the settings and modes of each luminaire. Estimating the energy consumption of the server was challenging due to a broad range of servers available. In our case a server with a performance of 50W (Joel Hruska, 2012), is used. The performance of 50W is only achieved if the server is fully load. Assuming a load of approximately 30% lead to the following equation 12.

$$P = 50W, ECIS_y = 0.3 \times 50W \times 24hours \times 365days \tag{12}$$

For usage of the lighting management system a computer in form of a tablet or PC is needed. Considering that the latter is more portable, considering a tablet for the management, with an iPad 2 from Apple. Its performance is 3,16W with display on and 0,45W in sleeping mode (Apple, 2012). Assuming two hours per day of usage of the lighting management, the energy consumption of the tablet was calculated according to the following equation 13.

$$ECCom_y = [\, 3,16W \times 2h + 0,45W \times 22h \,] \times 365days \tag{13}$$

$ECCom_y$ = Power consumption of the computer per year [Wh/year]

All equations explained were used to calculate the values of the energy flows and can be found in detail in the annexes.

3.6 Calculation of Flows in the Conventional LED Lighting System

For comparability of both systems, for the conventional LED the same luminaire was used with the only difference, that it is operating without the additional electrical devices such as motion sensors, controllers, radars, computers, and servers.

Due to the fact, that no electronical devices are used, the only way to operate the luminaires is throughout fixed settings. The intensity is constant at 70%. Based on that the energy consumption of a luminaire was computed according 14 and 15:

$$EC_{dj} = h_f \text{ x } t_{I = 70\%} \tag{14}$$

$$ECL_y = \sum_{j=1}^{3} \frac{365}{4} \times EC_{d,j} \tag{15}$$

The flow 'Energy Supply' is equal to the value of 'ECL_y'. The transmission and heat losses were calculated according to equation 16 and are equal to the value of the flow 'Energy Losses' leaving the process 'luminaire'.

$$Losses = ECL_y \times \frac{32.5\%}{100} \tag{16}$$

Setting up the equation (Annex) for each process of the luminaires leads to the values of the flows 'Emitted Energy' leaving the process 'luminaire'.

3.7 Assessment Indicators of Resource Efficiency

The two energy flow models of the conventional LED lighting system and the smart lighting system facilitate an analysis by comparing the two models with the help of assessment indicators. A commonly used assessment indicator is the transfer coefficient. The transfer coefficient describes the partitioning of the input flow of the substance energy within a process x in output flow j.

Because of the issue, that the luminaire used is the same in the conventional and the smart lighting system, the energy losses due to transmission and heat losses are also of the same magnitude. Moreover, having a steady-state system requires to assess the resource efficiency on another basis than on the transfer coefficient.

Another indicator, which facilitated to assess the efficiency in energy is to compare the energy input from the process 'distribution grid' to the processes of the luminaires and in case of the smart system also to the additional electronical devices. A direct comparison of the energy flow 'Energy Supply' between the two systems was performed.

3.8 Scaling up: Opportunity for Savings

The purpose of the case study on lighting systems is to illustrate the development of the energy flows in different scaling up scenarios. It was considered that the average number of lamps and sensors would be equal to the case study boundaries of 2.5 km.

The equation for calculating the quantities needed for each scaling up scenario is done according to the following equations:

$$Segment\ controllers\ needed = \frac{1\ segment\ controller}{150\ luminaires} \times number of Luminaires$$

$$Controllers\ needed = number\ of\ luminaires$$

$$Radars\ needed = \frac{4\ radars}{10\ luminaires} \times number of Luminaires$$

$$Servers\ capacity\ needed = \frac{1\ server\ capacity}{1000\ luminaires} \times number of Luminaires$$

$$omputers\ needed = \frac{1\ computer}{1000\ luminaires} \times number of Luminaires \tag{17}$$

The internal server's capacity needed stays constant, hence it is independent from the number of luminaires

needed, the increased amount of processing power needed was translated in increasing servers used. For computers was used the same methodology with one more table per 1000 luminaires. Tables 11 and 12 shows the number of items needed for the conventional and smart lighting system respectively.

Table 11. Quantities of each element in different scaling up scenarios in comparison [-] (Produced by the authors, 2017)

System	Conventional lighting system			
	1st scenario	2nd scenario *The commune of Ecublens*	3rd scenario *Half of all residential streets in Switzerland*	4rd scenario *All residential streets of Switzerland*
Luminaires	10	1050	103 700	207 400
Radars	-	-	-	-
Controllers	-	-	-	-
Segment controllers	-	-	-	-
Internal server	-	-	-	-
Computers	-	-	-	-
Total quantity	**10**	**1050**	**103 700**	**207 400**

Table 12. Quantities of each element in different scaling up scenarios in comparison [-] (Produced by the authors, 2017)

System	Smart lighting system			
	1st scenario	2nd scenario *The commune of Ecublens*	3rd scenario *Half of all residential streets in Switzerland*	4th scenario *All residential streets of Switzerland*
Luminaires	10	1050	103 700	207 400
Radars	4	420	41 480	82 960
Controllers	10	1050	103 700	207 400
Segment controllers	1	7	691	1 383
Internal server	1	1	104	207
Computers	1	1	104	207
Total quantity	**27**	**2529**	**249 779**	**499 557**

Calculation of the Scaling up flows in the smart lighting system:

$$F_{DG,Li} = 1,542,406.05 \, kJ \times number of Luminaires$$
$$F_{DG,Ri} = 4,801.36 \, kJ \times number of Radars$$
$$F_{DG,Coi} = 23,652 \, kJ \times number of Controller$$
$$F_{DG,SC} = 23,652 \, kJ \times number of Segment controllers$$
$$F_{DG,Com} = 21,313.08 \, kJ \times number Computer$$

Calculation of the Scaling up flows in the conventional lighting system:

$$F_{DG,Li} = 1.892.160,0 kJ \times number of Luminaires \tag{18}$$

When considering costs, since both luminaires are the same, and ceteris paribus for all other conditions, the cost of replacement parts should be the same. The maintenance cost is lower on the interoperable network because the problem is already known through the interface, this reduces maintenance time. The employee/hour dedicated to managing the system through the interface, was the same as the reduction in maintenance costs.

For the system cost it was multiplied the most expensive luminaire (CHF 572 and CHF 400 for smart and conventional luminaires) by the number of luminaires in each of the four models, adding the electricity consumption per year in kWh, that was multiplied by the electricity cost for industrial users in Vaud of CHF 0.1496 per kWh (Romande Energie, 2015). Then it was calculated the difference between the smart and conventional lighting costs, and modelling, with the Excel solver tool for which year it would become zero (through the parameters where the years had to be bigger or equal than zero, and smaller than 23 years, all calculations and solver can be seen at the Excel spreadsheet 'Excel Model' sent as attachment), to calculate the ROI, later it was calculated on 23 years the return.

Similar calculation was developed for the carbon equivalent emission, considering 33 gCO_2/kWh (Energy Scope, 2017) for energy produced in Switzerland and the difference between both smart and conventional lighting carbon equivalent emission per kWh consumed. Since the electricity distributed is not only generated in Switzerland, but it was also considered a second model using the data from the carbon equivalent emission of the Switzerland's energy current considering imports of 129 gCO_2/kWh (Energy Scope, 2017).

3.9 Sensitivity Analysis

One of the challenges was to estimate the number of passing items. Since this number influences the autonomous mode decisively a sensitivity analysis of the variable 'ItemPass' on the total energy consumption per year (TEC) was performed for four different scenarios. The four scenarios show an increase of 10%, 25%, 40% and 100% of the variable 'ItemPass'.

As the variable 'ItemPass' influences only the radars and luminaires energy consumption, the energy consumptions of the other processes remain constant.

1st Scenario: Increase of 10%   2nd Scenario: Increase of 25%

$$S_{10\%}^{(abs)} = \frac{\partial TEC}{\partial ItemPass} \qquad S_{25\%}^{(abs)} = \frac{\partial TEC}{\partial PassItem}$$

3rd Scenario: Increase of 40%   4th Scenario: Increase of 100%

$$S_{40\%}^{(abs)} = \frac{\partial TEC}{\partial PassItem} \qquad S_{100\%}^{(abs)} = \frac{\partial TEC}{\partial PassItem}$$

3.10 Considering the Additional Energy Consumption of the Electronical Devices Used

In case of having energy savings due to switching from a conventional lighting system to a smart lighting system, the additionally emerging energy consumption during the production of the electronical devices must be taken into consideration to facilitate an overall assessment from the environmental view.

4. Discussion

The energy flow model can be interpreted in different ways with changes in system boundaries. When considering the perspective of a commune, some of the processes are an externality and not calculated, such as the energy consumption of the internet used in the smart lighting system. The energy consumption of the internet is generally occurring at huge data centres of tech companies in Iceland or California for example.

One must keep in mind that making use of 'Internet of Things' includes a huge amount of energy at the data centres, which are difficult to measure. Figure 9 shows a Strengths, Weaknesses, Opportunities and Threats (SWOT) framework from different points of view emphasizing and scrutinizing the energy model itself and its results.
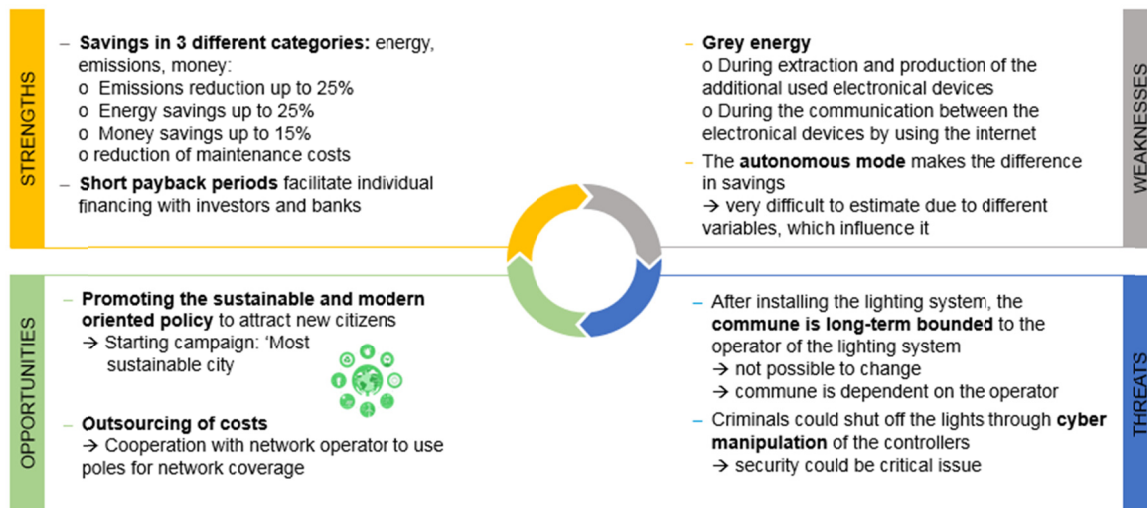

Figure 9. SWOT Framework (produced by the authors, 2017)

The system provides a reduced carbon footprint in both scenarios due to the reduction in energy, which also, through savings, mitigate the price difference between the luminaires, thus generating a return on investment, from the difference on savings. Another strength is the perception of the adopter on innovation, which may increase the awareness of the municipality and attract more inhabitants.

With governmental entities that might have debt, and the shift towards more energy saving products becomes more challenging, the financial return and image from innovation might attract cities, when already in the process of shifting to LED lighting, to choose the smart lighting system.

Another opportunity, which can be derived from the money savings in operating along the whole lifetime of a pole is the possibility to outsource the costs through a Public Private Partnership (PPP) or bank loans, whom might have benefits in investing in a more expensive system to profit from the energy savings. The smart lighting system might also create new sources of revenue, for example, Los Angeles partnered with the telecom provider AT&T to provide internet to clients through the poles, with the company increasing its coverage and paying for the city to use the infrastructure, the company is also creating electrical vehicles charging stations on poles (Maddox, 2016).

The energy flow model might not account for all externalities, such as the energy used for producing the electronic devices used to monitor the system, or for the internet production or data centres to store long-term data collection. Another variable is the number of items passing during the autonomous mode, since energy reduction is achieved through a decrease of passing items, it is therefore necessary to analyse for each street the major characteristics of district, the circumstances, and the inhabitants needs to enable a customized analysis and implementation of smart lighting systems.

As for the electronic devices used, when assessing energy consumption, the energy savings achieved from the usage of smart lighting in 23 years outpace the energy used for the devices production, but as for materials, some resources used are scarce (e.g., lithium). From the environmental point of view the production of the electronic devices must be not only analysed from a material or an energy flow perspective, but rather also from a water usage perspective. The extraction of noble earths included in these electronical devices expend a huge amount of water. In times of water scarcity, this issue should be also studied to derive an integral positive environmental assessment of smart lighting. A lifecycle and full supply chain analysis, including the transition costs, regarding the material flow of a smart lighting transaction could be object of further studies.

Considering that smart lighting systems (both autonomous and interoperable) have digital communications implied, the systems could be hacked, impacting on the city illumination. It's necessary to increase digital security of those systems regularly to prevent attacks. Another threat is the long-term project status, where cities might not be willing to engage in long term activities and changes in government might create conflicts for the provider, even where contracts are in place.

5. Conclusion

This project focused on evaluating the energy consumption of LED street lighting, comparing smart and conventional systems, to assess how clean technologies innovation address the issues they propose to solve. It's shown that smart lighting systems reduces the overall energy consumption even though there are more electrical equipment installed and in use, versus traditional lighting systems.

With countries trying to reduce, through policy making, the use of energy, LED lighting for streets might be used as a new alternative, and as this research shows, the energy savings from the smart lighting systems pays the price difference from the conventional LED lighting system off through the savings in electrical consumption. Considering finances, some cases show the possibility of increasing the source of revenue, through WiFi connection on poles, or electrical vehicles charging stations, which brings even further financial results of adopting this new technology.

In terms of energy savings, smart lighting systems reduces over 14% with a 10 lights system and 17% for 207 400 lights, when comparing to the regular LED systems, this savings brings not only financial results, but also CO2eq reduction, especially when considering the Switzerland energy mix with imports from high emitting sources. Therefore, a transition to smart lighting systems can improve the environmental sustainability of cities.

As for the downside, smart lighting is a tailor-made process, and every street should be evaluated for its potential. Since trees, houses, garages, crosswalks, cars passing (e.g., proximity to a hospital or police station might increase the traffic during the night time), and/or events can change the system structure, with an increased need for sensors, for example, or when it's not possible to use the smart lighting system due to the complexity. Municipalities should use smart lighting systems where there's the most possibility for impact, where dimming

the lights can be optimal and flows of items passing somehow controlled, like paths and parks.

For achieving a sustainable status, one must account for externalities. For the smart lighting system to be possible it's necessary to have more equipment and materials involved, and this needs to be taken into consideration. When going through the supply chain and considering the energy consumption for the production and usage phases of smart and regular LED lighting systems, the dimming from smart lighting still have an overall reduction in energy consumption, which shows that the transition to smart lighting system is overall more environmentally sustainable.

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Appendix A

Calculations on the Smart Lighting System

<u>Step 1</u>

The night hours are calculated as a mean for each of the four seasons according to the following equation:

$$n_j = \sum_{i=1}^{3} \frac{m_t}{d_i} \qquad (1)$$

nj = the mean of night hours per day for seasonj

mt = total night hours in monthi

di = days in monthi

	Mean of night hours per day	Autonomous mode (fixed despite season)	Fixed settings mode = night hours – autonomous mode
Winter	14,47 ≈ 14	9 hours	5 hours (1*)
Spring	10,87 ≈ 11	9 hours	2 hours (1**)
Summer	9,56 ≈ 10	9 hours	1 hour (1***)
Fall	12,68 ≈ 13	9 hours	4 hours (1****)

$$h_a = 9 \; hours \qquad (2)$$

<u>Step 2</u>

The total energy consumption per year of radars based on the assumptions done before is calculated according to the following equation:

$$ECR_y = n \times 365 \; days \times 9 hours \left(DetecEnerg \times \frac{ItemPass \times 1,5s \times 1h}{3600s} + ConstantEnergy \right) \qquad (3)$$

$$ECR_y = 2 \times 365 \; days \times 9 hours \left(0.6W \times \frac{12 \times 1,5s \times 1h}{3600s} + 0.2W \right)$$

$$ECR_y = 1333.71 \frac{Wh}{year} = 4801.36 \frac{kJ}{year} \tag{4}$$

ECR_y = Energy consumption of the radars per year

n = Number of radars used

DetecEnergy = Additional energy consumption because of detected item

ConstantEnergy = Constant energy consumption despite item detected or not

➜ ECR_y equal to flow 'Energy Supply' and 'Energy Emitted' for each radar i={1,2,3,4}

Step 3

Scaling: The necessary equation to calculate the performance dependent on the intensity is:

$$P_i = MinP + MaxP \times \frac{I}{100} \tag{5}$$

$$I = \{10,20,30,40,50,60,70,80,90\}$$

$$
P(I) = \begin{cases}
P=0W, I=0\% \\
P=60W, I=10\% \\
P=70W, I=20\% \\
P=80W, I=30\% \\
P=90W, I=40\% \\
P=100W, I=50\% \\
P=110W, I=60\% \\
P=120W, I=70\% \\
P=130W, I=80\% \\
P=140W, I=90\% \\
P=150W, I=100\%
\end{cases}
$$

$$\tag{6}$$

I_i = Intensity in per cent [%]

MinP = Minimal available performance [W]

MaxP = Maximal available performance [W]

Step 4

Calculating the general formula for each luminaire is:

$$t_{\approx I=100\%} = ItemPass \times \frac{1.5s}{ItemPass} \times \frac{1h}{3600s} \tag{7}$$

$$t_{I=40\%} = 1hour - t_{\approx I=100\%} \tag{8}$$

$$t_{\approx I=100\%} = 12 \times 1.5s \times \frac{1h}{3600s} = 0.005h \tag{9}$$

$$t_{I=40\%} = 1hour - t_{\approx I=100\%} = 0.995h \tag{10}$$

$t_{\approx I=100\%}$ = Duration of passing items at light intensity ≈ 100%

$t_{I=40\%}$ = Duration at light intensity 40%

Step 5

The energy consumption for the four representative nights for each season can be calculated according the following equation:

Insert (1*),(1**),(1***),(1****), (2),(5),(9),(10) into (11)

$$EC_{dj} = h_a \times (t_{I=40\%} \times P_{I=40\%} + t_{\approx I=100\%} \times P_{I=100\%}) + h_f \times P_{I=70\%} \tag{11}$$

$EC_{d, winter}$ = 9hours x (0.995hours x 90W + 0.005hours x 150W) + 5hours x 120W = 1412.7Wh

$$EC_{d, winter} = 5085.72 \text{ kJ/day} \tag{12}$$

$EC_{d, spring}$ = 9hours x (0.995hours x 90 W+ 0.005hours x 150W) + 2hours x 120W = 1052.7Wh

$$EC_{d,\ spring} = 3789.72 \text{ kJ/day} \tag{13}$$

$EC_{d,\ summer}$ = 9hours x (0.995hours x 90W + 0.005hours x 150W) + 1hour x 120W = 932.7Wh

$$EC_{d,\ summer} = 3357.72 \text{ kJ/day} \tag{14}$$

$EC_{d,\ fall} = $　9hours x (0.995hours x 90W + 0.005hours x 150W) + 4hours x 120W = 1292.7Wh

$$EC_{d,\ fall} = 4653.72 \text{ kJ/day} \tag{15}$$

h_a = hours in autonomous mode

h_f = hours in fixed settings mode

$EC_{d,j}$ = Energy consumption per day in season j per luminaire

Step 6

The final consumption per year of each luminaire:

Insert (12), (13), (14), (15) into (16)

$$ECL_y = \sum_{j=1}^{3} \frac{365}{4} \times EC_{d,j} \tag{16}$$

$$ECL_y = \frac{365}{4} \times (5085.72kJ + 3789.72\text{kJ} + 3357.72\text{kJ} + 4653.72 \text{ kJ})$$

$$ECL_y = 1{,}540{,}927.8 kJ/year \tag{17}$$

ECL_y = Energy consumption throughout the whole year per luminaire [kJ/year]

$EC_{d,\ j}$ = Energy consumption per night in season$_j$ per luminaire[kJ/day]

➔　*ECL_y* equals the value of the flows 'Energy Supply' to each luminaire

Step 7

The amount of energy wasted is calculated as the percentage of the energy demand of each LED luminaire. Insert (17) into (18):

$$Losses = ECL_y \times \frac{32.5\%}{100} \tag{18}$$

$$Losses = 1{,}540{,}927.8\ kJ \times \frac{32.5\%}{100} = 500{,}801.54\ kJ \tag{19}$$

➔　value of 'Losses' is equal to the value of the flows 'Energy Losses' leaving each luminaire *for all* $10\ luminaires\ i = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$.

The flow 'Energy Emitted' leaving each lumianaire, which represents the emitted light of the luminaires was calculated through setting up the equations for the in-and output flows for a luminaire.

$$\frac{dLuminaire}{dt} = Energy\ Supply_{DG,L1} - Energy\ Emitted_{L1,e} - Energy\ Losses_{L1,e} = 0$$

$$Energy\ Emitted_{L1,e} = Energy\ Supply_{DG,L1} - Energy\ Losses_{L1,e} \tag{20}$$

Step 8

The energy supply and consumption for each controller (LuCo) on a luminaire:

$$ECC_y = 0.75W \times 24 \times 365 \tag{21}$$

$$ECC_y = 0.75W \times 24hours \times 365days = 6570Wh = 23652\ kJ/year \tag{22}$$

ECC_y = Energy supply and consumption of controller per year

➔　The value of 'ECC_y' equals the flows 'Energy Supply' and 'Energy Emitted' for each radar i={1,2,3,4}

Step 9:

The energy supply and consumption for the segment controller:

$$ECSC_y = ECC_y = 23652\ kJ \tag{23}$$

$ECSC_y$ = Energy Consumption of a segment controller per year [Wh]

➔   The value of 'ECSC$_y$' equals the flows 'Energy Supply' and 'Energy Emitted' of the process segment controller

Step 10:

The energy supply and consumption per year:

$$ECCom_y = [\,3.16W \times 2h + 0.45W \times 22h\,] \times 365days \qquad (24)$$

$$ECCom_y = [\,3.16W \times 2h + 0.45W \times 22h\,] \times 365days = 5920,3\ Wh = 21{,}313.08\ kJ/year \qquad (25)$$

$ECCom_y$ = Power consumption of the computer per year [kJ/year]

➔   The value of 'ECCom$_y$' equals the flows '*Energy Supply*' and '*Energy Emitted*' of the process computer

Step 11:

The energy supply and consumption of the internal server:

$$P = 50W, ECIS_y = 50W \times 24hours \times 365days = 438.000\ Wh = 1{,}576.800\ kJ \times 0.3$$

$$= 473.040\ kJ \qquad (26)$$

➔   The value of 'ECIS$_y$' (26) equals the flows '*Energy Supply*' and '*Energy Emitted*' of the process '*Server*'

EFA Model: Smart lighting system

| Process$_i$	Abbreviation
Distribution grid	DG
Controller	Coi, i={1,2,3,4,5,6,7,8,9,10}
Segmentcontroller	SC
Luminaire + Driver + Motion Sensor 1	L1
Luminaire + Driver 2	L2
Luminaire + Driver 3	L3
Luminaire + Driver 4	L4
Luminaire + Driver 5	L5
Luminaire + Driver 6	L6
Luminaire + Driver 7	L7
Luminaire + Driver 8	L8
Luminaire + Driver 9	L9
Luminaire + Driver + Motion Sensor 10	L10
Radar	Ri, i={1,2,3,4}
Internal server	IS
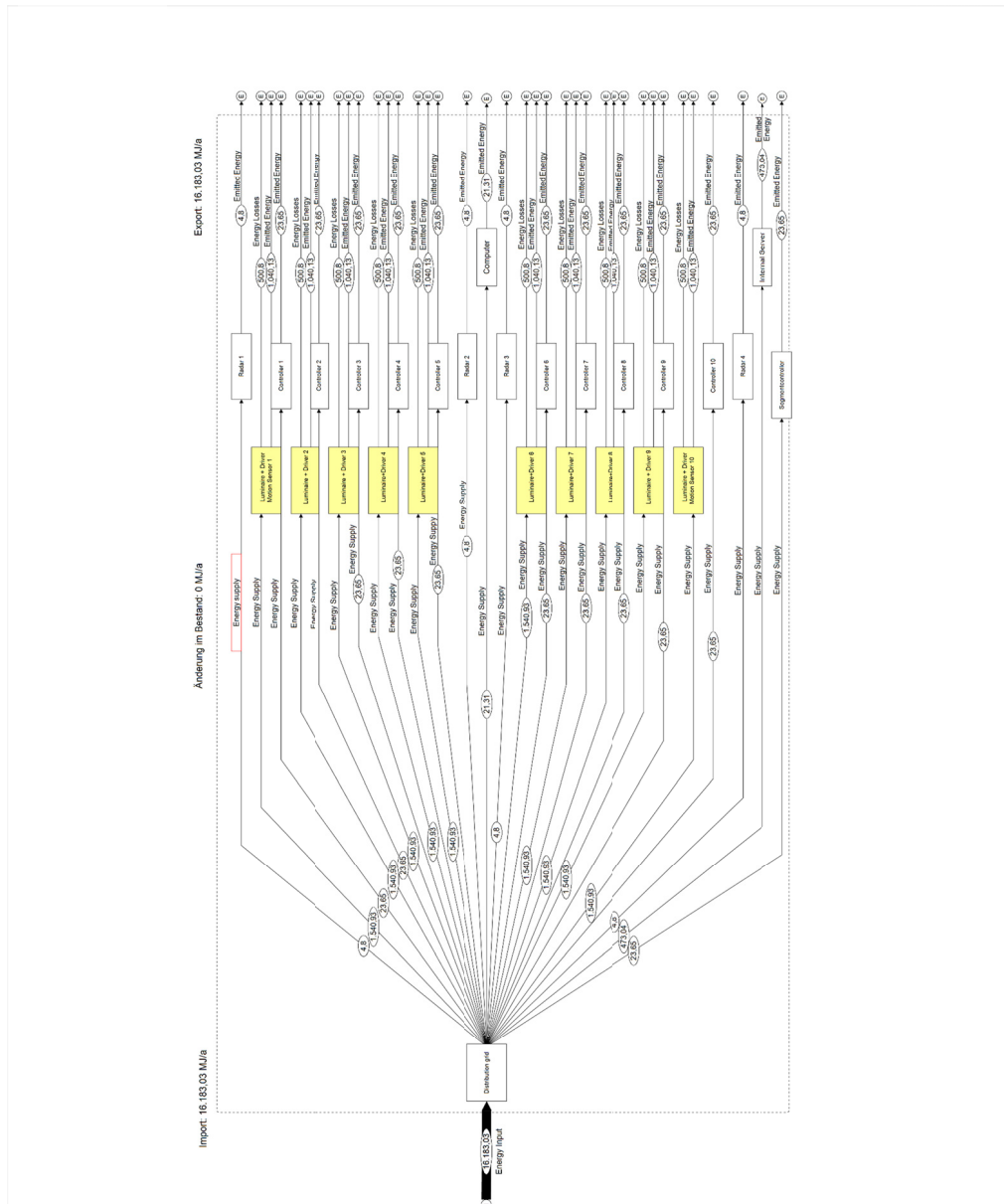
Figure 1. Energy Flow Model (Produced by the authors, 2017)

Appendix B

Conventional Lighting System

<u>**Step 1:**</u>

The conventional lighting system is constant at 80% in the fixed setted mode;

Insert (1*), (1**), (1***), (1****) into (1):

$$EC_{dj} = h_f \times P_{I=70\%} \tag{1}$$

$$EC_{d,\ winter} = 14 \text{hours} \times 120\text{W} = 1680\text{Wh} = 6048 \text{ kJ} \tag{2}$$

$$EC_{d,\ spring} = 11 \text{hours} \times 120\text{W} = 1320\text{Wh} = 4752 \text{ kJ} \tag{3}$$

$$EC_{d,\ summer} = 10 \text{hours} \times 120\text{W} = 1200\text{Wh} = 4320 \text{ kJ} \tag{4}$$

$$EC_{d,\ fall} = 13 \text{hours} \times 120\text{W} = 1560\text{Wh} = 5616 \text{ kJ} \tag{5}$$

Insert (2), (3), (4), (5) into (6):

$$ECL_y \;=\; \sum_{j=1}^{3} \frac{365}{4} \;\times\; EC_{d,j} \tag{6}$$

$$ECL_y \;=\; \frac{365}{4} \times \; [\, 6048\, kJ + 4752\, kJ + 4320\, kJ + 5616\, kJ\,] = 1{,}892{,}160.0\, kJ \tag{7}$$

➜ Value (7) equals flows $Energy\ Supply_{DG,Li}$ to each luminaire

$$i = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$$

Step 2:

Therefore, the transmission or heat losses were calculated also according equation (8).

$$Losses = ECL_y \;\times\; 32.5\% \;\times\; 100 \tag{8}$$

$$Losses = 1{,}892{,}160.0 \; kJ \;\times\; \frac{32.5\,\%}{100} = 614{,}952.0\, kJ$$

➜ value of 'Losses' is equal to the value of the flows $Energy\ Losses_{Li,e}$ $for\ i = \{1,2,3,4,5,6,7,8,9,10\}$ leaving each Luminaire

The flows $Energy\ Emitted_{Li,e}$ $for\ i = \{1,2,3,4,5,6,7,8,9,10\}$, which represent the emitted light of the luminaires, was calculated through setting up the equations for the in-and output flows for one luminaire.

$$\frac{dLuminaire}{dt} = Energy\ Supply_{DG,L1} - \ Energy\ Emitted_{L1,e} - Energy\ Losses_{L1,e} = 0$$

$$Energy\ Emitted_{L1,e} = \ Energy\ Supply_{DG,L1} - \ Energy\ Losses_{L1,e} \tag{9}$$

$$Energy\ Emitted_{L1,e} = 1\,277\,208\, kJ/year$$

EFA Model: Conventional lighting system

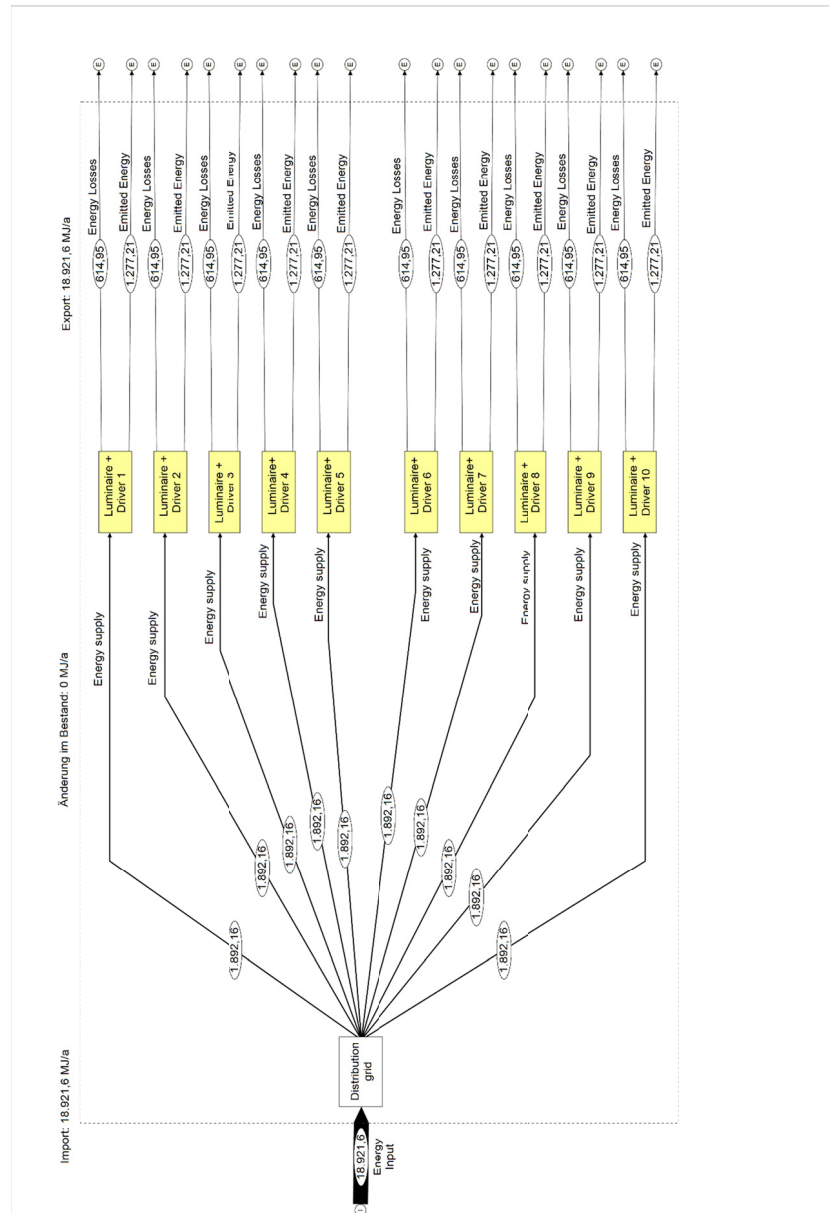| Process$_i$	Abbreviation
Distribution grid	DG
Luminaire + Driver 1	L1
Luminaire + Driver 2	L2
Luminaire + Driver 3	L3
Luminaire + Driver 4	L4
Luminaire + Driver 5	L5
Luminaire + Driver 6	L6
Luminaire + Driver 7	L7
Luminaire + Driver 8	L8
Luminaire + Driver 9	L9
Luminaire + Driver 10	L10

Figure 2. Conventional Smart Lighting Energy Flow (Produced by the authors, 2017).

Appendix C

Scaling Up for Both Systems

The equation for calculating the quantities needed for each scaling up scenario is done according the following equation:

$$Segment\ controllers\ needed = \frac{1\ segment\ controller}{150\ luminaires} \times number\ of\ Luminaires$$

$$Controllers\ needed = number\ of\ luminaires$$

$$Radars\ needed = \frac{4\ radars}{10\ luminaires} \times number\ of\ Luminaires$$

$$Servers\ capacity\ needed = \frac{1\ server\ capacity}{1000\ luminaires} \times number\ of\ Luminaires$$

$$Computers\ needed = \frac{1\ computer}{1000\ luminaires} \times\ number\ of\ Luminaires \tag{10}$$

Table 1. Quantities of each element in different scaling up scenarios in comparison [-]

System	Conventional lighting system			
	1st scenario	*2nd scenario* *The commune of Ecublens*	*3rd scenario* *Half of all residential streets in Switzerland*	*4rd scenario* *All residential streets of Switzerland*
Luminaires	10	1050	103 700	207 400
Radars	-	-	-	-
Controllers	-	-	-	-
Segment controllers	-	-	-	-
Internal server	-	-	-	-
Computers	-	-	-	-
Total quantity	**10**	**1050**	**103 700**	**207 400**

Table 2. Quantities of each element in different scaling up scenarios in comparison [-]

System	Smart lighting system			
	1st scenario	*2nd scenario* *The commune of Ecublens*	*3rd scenario* *Half of all residential streets in Switzerland*	*4th scenario* *All residential streets of Switzerland*
Luminaires	10	1050	103 700	207 400
Radars	4	420	41 480	82 960
Controllers	10	1050	103 700	207 400
Segment controllers	1	7	691	1 383
Internal server	1	1	104	207
Computers	1	1	104	207
Total quantity	**27**	**2529**	**249 779**	**499 557**

Calculation of the Scaling up flows in the smart lighting system:

$$F_{DG,Li} = 1.540.927{,}8\ kJ \times\ number of Luminaires$$
$$F_{DG,Ri} = 4.801{,}36\ kJ \times\ RadarsNeeded$$
$$F_{DG,Coi} = 23.652\ kJ \times\ number of Luminaires$$
$$F_{DG,SC} = 23.652\ kJ \times\ ControllersNeeded$$
$$F_{DG,Com} = 21.313{,}08\ kJ \times\ ComputersNeeded$$
$$F_{DG,IS} = 473.040\ kJ \times\ ServersCapacityNeeded$$

Calculation of the Scaling up flows in the conventional lighting system:

$$F_{DG,Li} = 1.892.160{,}0 kJ \times\ number of Luminaires \tag{11}$$

Table 3. Energy consumption [kJ/y] of each process in different scaling up scenarios in comparison

System	Conventional lighting system - Energy Consumption			
	1st scenario	*2nd scenario* *The commune of Ecublens*	*3rd scenario* *Half of all residential streets in Switzerland*	*4th scenario* *All residential streets of Switzerland*
Luminaires	18 921 600	1 968 768 000	196 216 992 000	392 433 984 000
Radars	-	-	-	-
Controllers	-	-	-	-
Segment controllers	-	-	-	-
Internal server	-	-	-	-
Computers	-	-	-	-
Total energy consumption	**18 921 600**	**1 968 768 000**	**196 216 992 000**	**392 433 984 000**

Table 4. Energy consumption [kJ/y] of each process in different scaling up scenarios in comparison

System	Smart lighting system – Energy Consumption			
	1st scenario	*2nd scenario* *The commune of Ecublens*	*3rd scenario* *Half of all residential streets in Switzerland*	*4th scenario* *All residential streets in Switzerland*
Luminaires	15 409 278	1 617 974 190	159 794 212 290	319 588 425 700
Radars	19 205	2 016 571	199 160 413	398 320 826
Controllers	236 520	24 834 600	2 452 712 400	4 905 424 800
Segment controllers	23 652	165 564	16 351 416	32 702 832
Internal server	473 040	496 692	49 054 248	98 108 496
Computers	21 310	22 378,73	2 216 560	4 411 810
Total energy consumption	**16 183 005**	**1 645 509 996**	**162 513 707 300**	**325 027 394 500**

Appendix D

Sensitivity Analysis on passing items

Step 1

The hours in which the smart lighting system operates in the autonomous mode stays constant.

$$h_a = 9 \ hours \tag{1}$$

Step 2

The total energy consumption per year of a radar in the three scenarios:

$$ECR_y = n \times 365 \ days \times 9 hours \left(DetecEnerg \times \frac{ItemPass \times 1.5s \times 1h}{3600s} + ConstantEnergy \right) \tag{2}$$

1st scenario: 10% increase of variable 'ItemPass'

$$ECR_y = 2 \times 365 \ days \times 9 hours \left(0.6W \times \frac{12 \times 1.10 \times 1.5s \times 1h}{3600s} + 0.2W \right) = 4808.45 \ \frac{kJ}{year} \tag{3}$$

2nd scenario: 25% increase of variable 'ItemPass'

$$ECR_y = 2 \times 365 \ days \times 9 hours \left(0.6W \times \frac{12 \times 1.25 \times 1.5s \times 1h}{3600s} + 0.2W \right) = 4819.1 \ \frac{kJ}{year} \tag{4}$$

3rd scenario: 40% increase of variable 'ItemPass'

$$ECR_y = 2 \times 365 \ days \times 9 hours \left(0.6W \times \frac{12 \times 1.40 \times 1.5s \times 1h}{3600s} + 0.2W \right) = 4829.74 \ \frac{kJ}{year} \tag{5}$$

4th scenario: 100% increase of variable 'ItemPass'

$$ECR_y = 2 \times 365 \ days \times 9 hours \left(0.6W \times \frac{12 \times 2 \times 1.5s \times 1h}{3600s} + 0.2W \right) = 4872.312 \ \frac{kJ}{year} \tag{6}$$

Step 3

The variable 'ItemPass' influences the duration of each intensity:

$$t_{\approx I=100\%} = ItemPass \times \frac{1.5s}{ItemPass} \times \frac{1h}{3600s} \tag{7}$$

$$t_{I=40\%} = 1 hour - t_{\approx I=100\%} \tag{8}$$

1st scenario: 10% increase of variable 'ItemPass':

$$t_{\approx I=100\%} = 12 \times 1.1 \times 1.5s \times \frac{1h}{3600s} = 0.0055h$$

$$t_{I=40\%} = 1 hour - t_{\approx I=100\%} = 0.9945h$$

2nd scenario: 25% increase of variable 'ItemPass'

$$t_{\approx I=100\%} = 12 \times 1.25 \times 1.5s \times \frac{1h}{3600s} = 0.0063h$$

$$t_{I=40\%} = 1hour - t_{\approx I=100\%} = 0.9938h$$

3rd scenario: 40% increase of variable 'ItemPass'

$$t_{\approx I=100\%} = 12 \times 1.4 \times 1.5s \times \frac{1h}{3600s} = 0.007h$$

$$t_{I=40\%} = 1hour - t_{\approx I=100\%} = 0.993h$$

4th scenario: 100% increase of variable 'ItemPass'

$$t_{\approx I=100\%} = 12 \times 2 \times 1.5s \times \frac{1h}{3600s} = 0.01h$$

$$t_{I=40\%} = 1hour - t_{\approx I=100\%} = 0.99h$$

Step 5

The energy consumption for the four representative nights for each season has to be adjusted due to the change of the variable '$t_{\approx I=100\%}$':

$$EC_{dj} = h_a \text{ x } (t_{I=40\%} \text{ x } P_{I=40\%} + t_{\approx I=100\%} \text{ x } P_{I=100\%}) + h_f \text{ x } P_{I=70\%} \tag{9}$$

1st scenario: 10% increase of variable 'ItemPass':

EC$_{d, winter}$= 9hours x (0.9945hours x 90W + 0.0055hours x 150W) + 5hours x 120W = 5086.69kJ

EC$_{d, spring}$ = 3790.69 kJ

EC$_{d, summer}$ = 3358.69 kJ

EC$_{d, fall}$ = 4654.69 kJ

2nd scenario: 25% increase of variable 'ItemPass'

EC$_{d, winter}$ = 5088.54kJ

EC$_{d, spring}$ = 3792.53 kJ

EC$_{d, summer}$ = 3360.54 kJ

EC$_{d, fall}$ = 4656.54 kJ

3rd scenario: 40% increase of variable 'ItemPass'

EC$_{d, winter}$ = 5089.61 kJ

EC$_{d, spring}$ = 3793.61 kJ

EC$_{d, summer}$ = 3361.61 kJ

EC$_{d, fall}$ = 4657.61 kJ

4th scenario: 100% increase of variable 'ItemPass'

EC$_{d, winter}$ = 5095.44 kJ

EC$_{d, spring}$ = 3799.44 kJ

EC$_{d, summer}$ = 3367.44 kJ

EC$_{d, fall}$ = 4663.44 kJ

Step 6

Finally the energy consumption of each luminaire can be calculated:

$$ECL_y = \sum_{j=1}^{3} \frac{365}{4} \times EC_{d,j} \tag{10}$$

1st scenario: 10% increase of variable 'ItemPass':

$$ECL_y = \frac{365}{4} \times (5086.69kJ + 3790.69kJ + 3358.69kJ + 4654.69 \text{ kJ}) = 1,541,281.85 \frac{kJ}{year}$$

2nd scenario: 25% increase of variable 'ItemPass':

$$ECL_y = \frac{365}{4} \times (5088.54kJ + 3792.53kJ + 3360.54kJ + 4656.54\,kJ) = 1,541,956.19\ kJ/year$$

3rd scenario: 40% increase of variable 'ItemPass':

$$ECL_y = \frac{365}{4} \times (5089.61\,kJ + 3793.61\,kJ + 3361.61\,kJ + 4657.61\,kJ) = 1,542,347.65\,kJ/year$$

4th scenario: 100% increase of variable 'ItemPass'

$$ECL_y = \frac{365}{4} \times (5095.44\,kJ + 3799.44\,kJ + 3367.44\,kJ + 4663.44\,kJ) = 1,544,475.60\,kJ/year$$

ECL_y = Energy consumption throughout the whole year per luminaire [W/year]

$EC_{d,j}$ = Energy consumption per night in season$_j$ per luminaire[W/day]

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