DIRECT CURRENT IN PUBLIC LIGHTING FOR IMPROVEMENT IN LED PERFORMANCE AND COSTS

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ABSTRACT

Public lighting's primary purpose is nighttime visibility for security and safety. How to meet so many requirements of so many stakeholders? The key to developing a good plan is to relate lighting to functions of public spaces, because street lighting is more than a technical requirement, a security need, or a design element. It can be thought of and utilized in terms of how the type, placement, and wattage affect how a street is perceived and used. With present-day used street lighting systems however, flexibility is expensive, as is maintenance and energy consumption. A new solution is to use LED lighting with a Direct Current power system. Advantages are a decrease in: energy conversions; material use; amount of switch-boxes; components; labour costs and environmental comfort. The overall implementation of LED and DC will result in better control and efficient maintenance due to integrated bidirectional communication. A challenge is the relatively high investment for these new solutions. Another challenge; DC is not a standard yet in rules and regulations.
In the paper the transition to direct current public lighting system will be described with all the pros and cons. A new concept of public ownership, to overcome financial challenges will be discussed.

Key words: innovation management, intelligent street lighting, direct current, LED lighting, service level agreement

1. INTRODUCTION

'DC – road to its full potential' is an educational and research programme initiated by The Hague University of Applied Sciences (THU). The programme started in February 2013 and the first part of the programme will end in January 2015. The programme is considered ambitious with its five objectives:

1. To gather, capture and create new knowledge on DC-systems, especially in the built environment.
2. To educate both THU students and THU staff in international and relevant projects.
3. To help our partners, especially SME's, in overcoming knowledge-related obstacles in innovation processes and introducing them to potential partners.
4. To continue and expand collaborative DC research and DC projects with universities: CPUT, South Africa, KU Leuven, Belgium, TU Delft, the Netherlands and industry partners.
5. To further the cause of sustainable electrical generation by stimulating innovative behaviour of students, staff and partners locally and internationally.

Two of the project partners are presently working on LED lighting concepts in combination with direct current (DC) power for public lighting purposes. Within the scope of 'DC – road to its full potential', THU and its partners have carried out several tests and measurements. The results of these experiments, placed within their context will be presented and discussed within this paper.

The field of public lighting is undergoing several changes in a short time span. Needs of its users and owners related to public lighting are changing, available technologies for both the lighting itself and the required infrastructure are changing as well.

The next chapter of this paper will start with a brief history of public lighting in Europe, focussing on the Netherlands. From this point, firstly the changing needs of its users and owners are discussed. Secondly, the paper presents an overview of techniques for lighting, related to the recent history. Especially LED technique is discussed. The result of the experiments will underline some of the benefits of LED lighting. Thirdly, the paper then proposes a new way to design, install and maintain the electrical infrastructure for public lighting using DC. In the last sector of this paper, the most important challenges, regarding public lighting with LED and DC are discussed. Where available, solutions to these challenges will be proposed and evaluated.

2. HISTORY OF STREETLIGHTS IN THE NETHERLANDS

In the Netherlands 1,5% of the produced electric energy goes to public outdoor lighting. The total energy consumption of outdoor lighting in the Netherlands is around 600 000-700 000 MWh/yr, from which 500 000 MWh is consumed by *public* outdoor lighting. The first form of public outdoor lighting in the Netherlands was in 1544 when a fixed candle lantern was placed in Amsterdam [1]. Started with candles, to oil lighting in the 17^{th} -18^{th} century, to gas lighting in the 19^{th} century until 1886 when electric lighting was introduced in the Netherlands. This later revolution kick-started the increase of lighting points in the Netherlands. During the Second World War the outdoor lighting was almost completely offline. Despite the scarcity in 1945 the outdoor lighting was started again later that year, as a sign of change and enlightenment. The quick restart confirms the positive relation between feeling secure and street lighting [2]. Public street lighting took off quickly after the war. That trend drove on, even into this century. Nowadays, more than 20% of highways in the Netherlands have lights, almost 700 km [3]. In Belgium even 90% of all highways have public lighting. Night-time satellite images clearly indicated borders with neighboring countries as France and Germany. These countries stayed a lot darker at night. In Germany for example, about 5% of all highways is illuminated. Even so, that represents a great length in lighted highway. Does this growth explain the present attention for energy use of public lighting?

Energy-usage awareness for public lighting is nothing new altogether. The first oil crisis in 1973 made the Dutch government reflect upon the energy consumption of street lighting. Energy saving measures were taken (i.e. belated switch on times), which were maintained after the crisis. In the late 20th century, motives were mostly financial. In the 21st century, sustainability joined in with these financial arguments. The Energy Agreement of the Social and Economic Council of the Netherlands (SER) stimulates an accelerated renovation of the current dated grid and lighting assets [4]. Public street lighting and traffic regulation should deliver energy savings of 20% in 2020 and 50% in 2030 compared to 2013. At least 40% of the street lighting installations should be supplied with intelligent energy management systems and energy-saving lighting.

3. THE NEED FOR AFFORDABLE INTELLIGENCE

The need for intelligent street lighting installations or systems is not solely driven by the Dutch National Energy Agreement, municipalities and citizens have the need for sized lighting. Citizens want to actively participate in the interpretation of the public environment. Polls in Eindhoven have shown that its inhabitants like to be able to influence and steer the street lights according to their needs [5]. Social safety and security are two important criteria for people on the streets. In the Hierarchy of Needs of Abraham Maslow [6] safety is the second step after basic physiological needs for the well-being of people, so it influences the development of people (figure 1). Street lighting plays a dominant role in the feeling of safety and security [7]. Providing the cities and their citizens with a perfectly sized light experience contributes to a safe and secure environment.

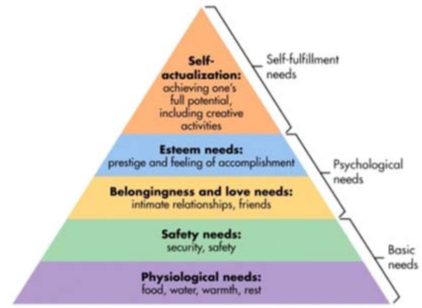

Figure 2: Maslow's Hierarchy of Needs

Municipalities in the Netherlands want to provide a safe, secure and sustainable environment for their citizens. But they have to deal with considerable costs to maintain street lighting and a high energy bill on one hand and budget cuts on the other. Also the process of reporting defects is out of balance and people have the need to know the real time status of their report, just like track and trace functionalities of online companies.

The past decade public street lighting started a transformation from a static system (on/off) towards a dynamic system. The availability of flexible lighting solutions is rising and street lighting transforms into an intelligent, energy-efficient, remotely monitored and steered system (figure 2). A lighting installation communicates through RF or power line communication with a management platform. Communication with the installation can happen on different levels and on different devices, guarded by a right structure. I.e. the owner can monitor and steer the installation with a program on his computer. While a citizen can switch on the lights with a smartphone application once near the light poles.

Flexible or intelligent lighting systems offer improvement over inflexible systems. Firstly, intelligent street lighting systems enable cities to determine a lighting schedule on individual or group level and meet the needs of the environment in terms of weather, festivities or occupancy

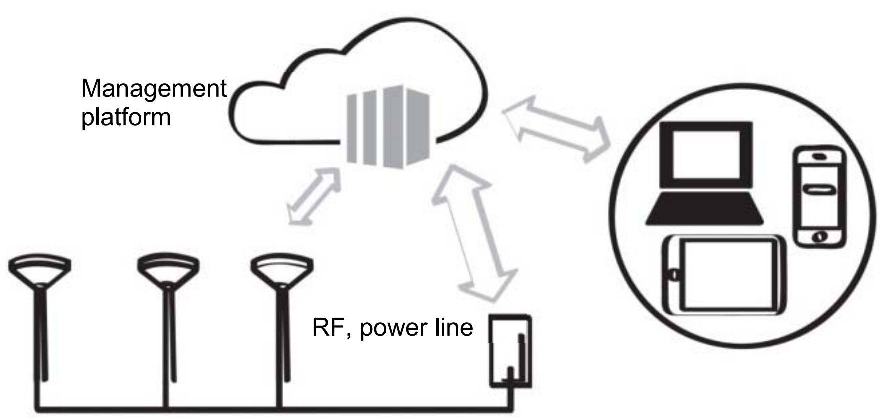

Figure 1: Intelligent street lighting system

at a certain time of day. Secondly, defects in the installation are reported directly into the system or citizens can report them in the system. The real time and detailed overview of the assets leads to proactive maintenance and real time information for all stakeholders. Thirdly, the energy management functionalities of the software provide cities with a clear overview of the energy consumption and enable them to reach their sustainability goals. This functionality facilitates decision making by showing the energy conservation when you exchange conventional lights for LED or when you apply another dim schedule.

In both the Netherlands and Belgium, national and regional governments decided to make public lighting more flexible. Experiments were carried out and new policies were implemented from 2011 (Belgium) and 2012 (Netherlands) [8]. These policies are resulting in investments in aging infrastructure, to be able to switch on and off manually or even automatically. Estimated savings for switching of larger parts of the public lighting on highways in the Netherlands add up to a total of € 34 million until 2020. It is not clear if these numbers include the needed extra investments for making the existing lighting infrastructure more flexible [9]. Savings for turning off public lighting on provincial and/or municipal roads in the Netherlands are yet unknown. An example from the city of Boston (MA) clearly states that significant savings are within reach. [10]

4. THE ARRIVAL OF LED TECHNOLOGY

Presently there is another transition going on in outdoor lighting: a transition from conventional gas (High Pressure Sodium, Mercury) lights towards LED lights. The application of LED in outdoor lighting is quite new. The first LED street lighting pilot projects in the Netherlands were realized in 2008-2010 [11], whereas LED technology itself was invented in 1962. The advantages of LED compared to conventional lighting are less energy consumption and a longer lifespan of the actual lights. For municipalities, these benefits might be translated into a lower energy bill and a decrease in installation and maintenance costs. The downside of this is that LED-lights still require higher investments. That means that LED's as a means for lighting are not yet cost efficient for every situation.

One of the first pilot DC street lighting projects is an installation of 75 new light poles on existing cables in Haarlemmermeer. The goal of this project is to realize an innovative and durable installation in a business area. An energy efficiency analysis of the current and future light sources was performed prior to the start of the project. Table 1 displays the energy consumption and savings of the current and future installation. The current situation is a combination of SOX 55W and 66W lights without a dim schedule. The future situation is with LED 36W lights and a dim schedule as shown in figure 3. The expected energy consumption of the LED lights is only one third of the consumption of the combination of SOX. This clearly underlines the energy efficiency benefits of LED compared to conventional light sources.

All this attention for LED lighting helps raising the question what LED lighting exactly is, specifically compared to more traditional forms of lighting. As mentioned earlier, in public lighting, gas or vapor lights are commonly used. In these lamps, gas is discharged to bring it to an exited state to emit photons and thus light. In simpler incandescent lamps, a wire is heated to make it glow. Light then is visible electromagnetic radiance because of the heat in the wire. Light from LED works differently:

A ***light-emitting diode (LED)*** *is a two-lead semiconductor source. It resembles a basic pn-junction diode, which emits light when activated. When a fitting voltage is applied to the leads, electrons are able to recombine with electron holes within the device, releasing energy in the form of photons, light.* [12]

This is where things get interesting, from the point of view of an electrical engineer. Semiconductors are the basis of modern (power) electronics. Semiconductors work on direct current, or DC. Common electrical installations, transmission and distribution grids however work on alternating current, AC. The war of the currents made sure of that. [13] That means that almost every LED of every group or cluster of LED needs an inverter, to make DC from AC.

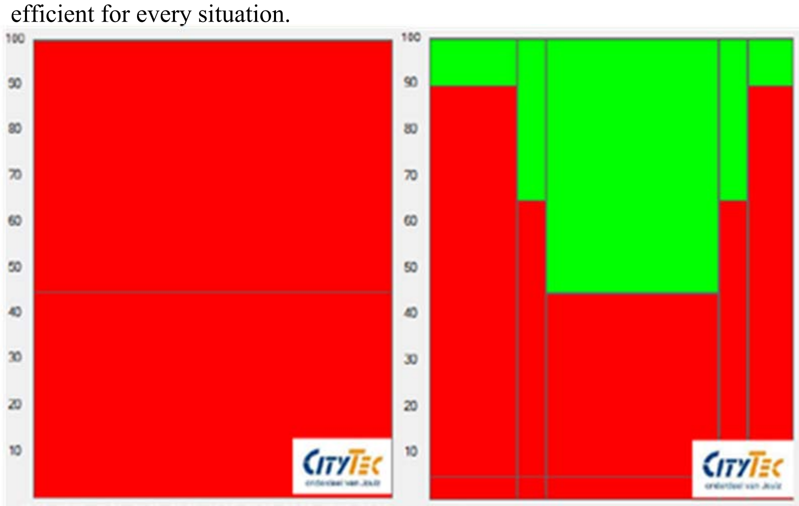

Figure 3: Left light schedule current situation (SOX), right light schedule future situation

	Present situation	Future situation
Normal energy consumption (kWh)	352	223
Energy consumption dim schedule (kWh)	352	123
Energy savings (kWh)	0	100
Energy savings (%)	0	44,7

Table 1: Measurements SOX 55W & 66W vs. LED 36W. (Energy consumption and savings measured on a yearly basis, excluding grid losses)

These electronics are presently a vulnerable part of LED installations. If LED installations were fed in with DC, these inverters might become much simpler (less components and materials) and more energy efficient.

5. SHIFT AC TO DC

In various research- and pilot projects in the Netherlands [14] and other parts of Europe, there is an increase in the application of DC as a means for distribution of electrical energy. This attention is driven by several, until now mostly assumed or theoretical, benefits of DC compared to AC. These benefits are:

- Reduction of (resistive) losses in cables and wires.
- Reduction of iron/core losses in transformers
- Decrease in material usage.
- Increase in lifespan of appliances
- Simplification of electrical installation

In the sections below, each of these benefits will be further explained. To start with the reduction in losses in cables and wires: DC only evokes an Ohmic resistance, whereas AC evokes an inductive reactance as well. Several DC projects propose to raise voltage levels for in-house distribution to 350 or even 380 VDC [15]. Higher voltages transferring the same power result in smaller currents, thus reducing losses. An important note here is that raising voltage levels on AC will also result in reduced losses. On identical voltage levels and working with identical cables, a DC-fed cable will always have less losses then an AC-fed one per distance.
Transforming or inverting power to different voltage levels, for example to use LED lighting, will always require a transformer (AC) or inverter (DC) (figure 4). An AC transformer uses far more iron for its core than a similar DC inverter. [13] These smaller cores result in smaller losses (both hysteresis and Eddy-current) while inverting. Using these smaller iron cores is a simple demonstration of the feasible savings in usage of raw materials. Arguing that needing more inverters in a DC infrastructure (because of all the sockets might require inverters, thus needing more iron) is no valid argument,

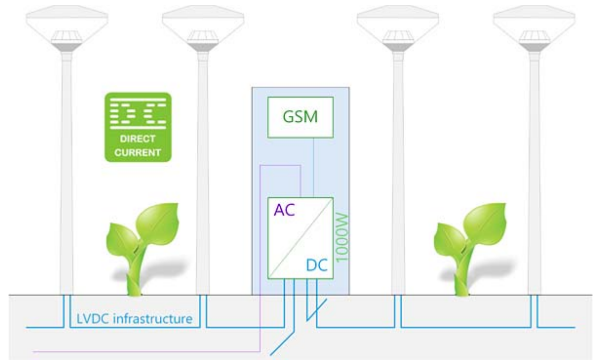

Figure 5: overview of a DC street lighting installation in an AC world [16]

simply because there are no guidelines or standards stating how a DC-electric infrastructure should be implemented. Figure 5 visualizes an AC and DC electrical for an average household consuming 3400 kWh. This example clearly indicates the extra losses in an AC system compared to DC, due to extra conversion steps, when coupled with sustainable, distributed generation.

Another point where serious material savings are within reach is with copper wires and cables. DC makes more effective use of all the material. That is the first argument to switch to thinner cables. A second and more important argument is that DC-power can and perhaps should be electronically controlled. That means, that short-circuit-power, which will not be needed, is no longer the means to calculate thickness of cables and wires.

Acceptable voltage drops per given distance will in the DC world become the most important means to calculate cable length and thickness. No longer calculating with short-circuit-power will have a far more significant impact on cable thickness, making them thinner and thus on material savings (figure 6, next page). A third point that is being made is much more difficult to prove.

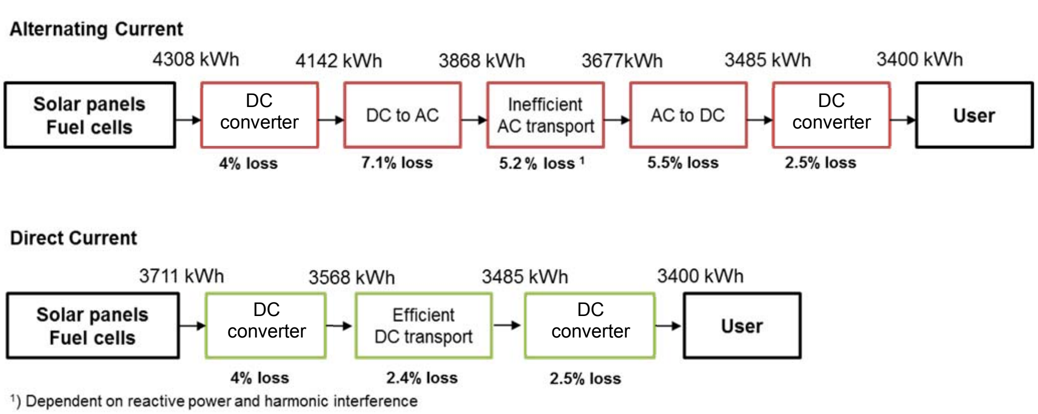

Figure 4: System losses in AC and DC grids

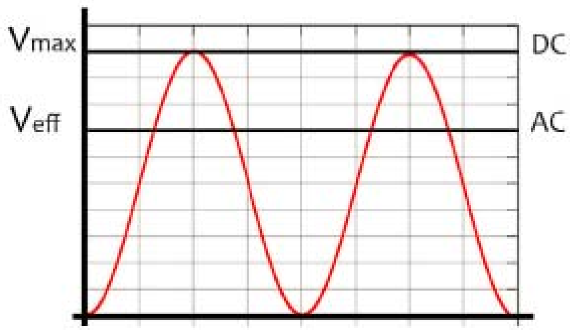

Figure 6: Voltage level variation AC vs DC [14]

Several parties state that working in an entirely DC-Grid, from generation to load, will require less transformations and thus less or simpler inverters. The main argument here is that for example pv-panels produce DC-power. If this DC power is transported as DC power towards DC loads (EV, LED's, consumer electronics) then the system can do without AC to DC transformation. That should result in less materials and components being used. It should also reduce transformation losses and thus improve system efficiency. The mentioned research and pilot projects are not yet able to proof this.

Distributing DC power might also improve the lifespan and performance of appliances. Several appliances, as televisions and computers already work on DC internally. Switching to DC makes these appliances simpler, because they no longer need to transform AC to DC. This transformation, using specific electrolytic capacitors, is in terms of lifespan, vulnerable to wear. Skipping the use of electrolytic capacitors, applications might be able to last twice as long. That has a tremendous impact on depreciation and thus on exploitation costs. [17] Electrical performance might increase two to three percent. [15] Next to this, some appliances with electrical motors or drives use frequency regulators, to allow them to work independent from AC-grid frequency. This regulator is the point to feed in DC power. This concept is not yet proven however.

The fifth and final assumed benefit is that DC offers different topology and solutions. Examples in the horticultural sector, [15] clearly state the reduction in copper and aluminum needed to implement an electrical installation. Because of electronically controlled lights, switchboards and related cables are no longer necessary. Using a bipolar bus instead of separate cable for every individual lamp, material usage drops dramatically, as stated earlier. Having to install less cable will not only reduce the needed cables, but it will also lower the needed labour, thus reducing the installation costs.

Pilot projects in public lighting, combining both LED and DC, indicate similar benefits:

- DC cables can cover larger distances, because of higher voltages and lower cable losses and because of the relatively modest energy consumption of the LED themselves. That means that more poles can be fed in from one single source / connection point. Installing fewer sources reduces installation and maintenance costs. DC-systems can also route power from neighboring sources to circumvent failure of single sources. That improves reliability of the system.
- Secondly, current and power is controlled electronically. Malfunction of lights will be detected immediately. The application will also be able to tell whether the lamp itself is failing or the electronics feeding into the lamp. Electronics are placed on ground level, to be easily reached by mechanics. Only lamp replacement will require the use of special maintenance vehicles.
- Thirdly, power line communication is used for steering the lamp as well, communication is bi-directional. Dimming and switching off entirely can be done from a control room, laptop or perhaps even a tablet or smartphone. Also the other benefits of intelligent street lighting systems can be achieved. Moreover power line communication is very suitable in a DC installation since there are no harmonic distortions.

6. CHALLENGES FACING DC GRIDS AND PUBLIC LIGHTING

Off course there are not solely benefits for a combination of DC and public street lighting. Two main challenges can be identified, first the investment barrier and second the standardization and electronic safety of DC.

6.1 INVESTMENT BARRIER TO NEW TYPE OF OWNERSHIP

The high investment and related depreciation costs of these intelligent public lighting installations are a barrier for municipalities. Municipalities are dealing with budget constraints, and as mentioned before there furthermore is a need for a more effective defect reporting and handling process. Financing the investment and, during the life time of the system, appropriated management and maintenance requires a new approach.

Firstly, a trend can be noticed in maintenance strategies: many municipalities and industries are changing their maintenance strategy from a reactive firefighting strategy, towards a proactive, preventive and predictive strategy [18]. Second, a shift is noticed in the Netherlands where responsibility for design decisions and maintenance of the installation or construction is shifting towards the contractor or service provider [19]. Table 2 shows the change in types of contracts and responsibility of the construction phases from traditional towards performance contracts.

	Traditional contracts			(long-term) Maintenance	Integrated solutions (performance contracts)	
Construction stage	Reimbursable contract	Unit price contract	Collaboration contract	Framework contract	Design & construct contract	Turnkey contract
Initiative						
Research	Responsibility: client					
Definition						
List of requirements						
Concept design						
Final design						
Execution design						
Process planning						
Execution				Responsibility: contractor / service provider		
Maintenance						

Table 2: Transition in responsibility and contracts [19]

Available software solutions and knowledge on intelligent street lighting offer effective means for a proactive management and maintenance strategy. Municipalities often do not have in-house knowledge and capacity to execute a proactive maintenance strategy. Therefore Service Level Agreements (SLA), mostly matched with finance or operating lease agreements, are offered to these municipalities.

- The SLA describes the performance indicators of the assets and implicates the service provided by the contractor (i.e. at least 99% of the installation needs to be online, defects need to be resolved within 48 hours) To be able to check the actual performance, management software is required. Operational benefits, specifically in maintenance, are to be secured here
- The lease contracts offer municipalities use and possible ownership of the innovative lighting solutions This type of financial service enables users to use assets without the need to provide all of the capital. The financer has sufficient access to equity to purchase assets and to lease them [20].

These coupled agreements together enable municipalities to profit from the proposed benefits of DC-fed LED-public lighting.

6.2 STANDARDIZATION AND ELECTRONIC SAFETY

Direct current currently is not yet extensively described in the standards like alternating current. In the Netherlands the NEN1010-standards cover the installation and usage of electricity (electric installations and low voltage) in the build environment. A third of the NEN1010 are general instructions, half of the standards concern AC and the small left over concerns DC [15]. There is no clear overview yet for DC, which makes people hesitant. On the other hand there is room for innovation and off course standards will come, the current NEN1010 does not fit anymore.

Safety plays an important role in standards. Most Dutch and International standards describe in detail, which safety precautions need to be taken to establish a prescribed level of safety. If you follow the standards strictly and adapt these precautions to a DC-system, one might end up with a very unsafe and uncontrollable system. Especially a mechanical means of switching of installations is difficult with DC, but not impossible at all.

There are other ways, using other techniques, to establish an identical level of safety. If you were able to use power electronics to switch off, DC systems might end up being very safe and usable. Once something is wrong in a DC system it is able to switch off in nanoseconds, even faster than AC. AC can also be switched off by means of this method. However this is not used frequently because the traditional method works sufficiently. The big injection of 2.3 million euro by the German Council of Education and Research [21] in research towards DC electronic circuit breakers underlines the importance and trust in a safe and usable result.

To create the standards for DC, different stakeholders (grid operators, manufacturers of cables etc. and the government) need to come together. This does not only concern the Dutch but also international standards. Once these standards are set, laws governing electricity distribution must be implemented. For the pilot projects the rules on AC and DC as described in the NEN1010 are followed. The main focus of these projects is: safety first, results second. So only DC educated technicians will be able to work on DC installations and special protection measures are taken into account.

At the moment of writing DC applications in public lighting are still in the trial phase, where the first three projects took off. In this phase bottlenecks will be documented and processes will be changed and shaped accordingly. Some knowledge is already available from projects in others areas like horticulture.

7. EVALUATION

In this paper three main drivers for change in public street lighting were discussed; sustainability, need for flexible lighting and financial savings. New techniques, including LED and communication offer new possibilities for municipalities and its inhabitants, whilst at the same time lowering the energy usage of lighting systems. This results in a desired lower electricity bill for Dutch municipalities. Municipalities producing their own electricity experience other benefits, perhaps being able to sell more electricity and thus making a profit or making better use of taxes paid by its inhabitants for social or economic support.

The combination of LED in street lighting with the advantages of a DC grid provides the market with an up to now optimal solution, at least on paper. These solutions have their downsides. Due to lacking tax incomes and economic growth national and regional governments in the Netherlands and other European countries, are lacking budgets for new investments. Investing in new installations, being AC or DC, requires more money than most municipalities have. Different ownership and control models help governments to overcome these obstacles.

Perhaps the biggest obstacle, not easy to overcome for a single municipality, is the lack of proper standards, suitable for DC. Several committees, for both Dutch and European standards are looking into DC as we speak. Lots of applied and fundamental research needs doing in the next few years, to support these new standards coming into existence. Research grants, for example from the German government however indicate that willingness to overcome this specific obstacle is present and growing.

As mentioned, three projects just started and are now in the realization phase. These pilot projects are realized and monitored by some of THU's partners. In the final quarter and first quarter of the next year partners are able to evaluate the installations. Realized energy-efficiency, first maintenance cycles and the overall performance of the system will be thoroughly looked into and possibly be studied in the next phase of the 'DC – road to its full potential' programme.

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