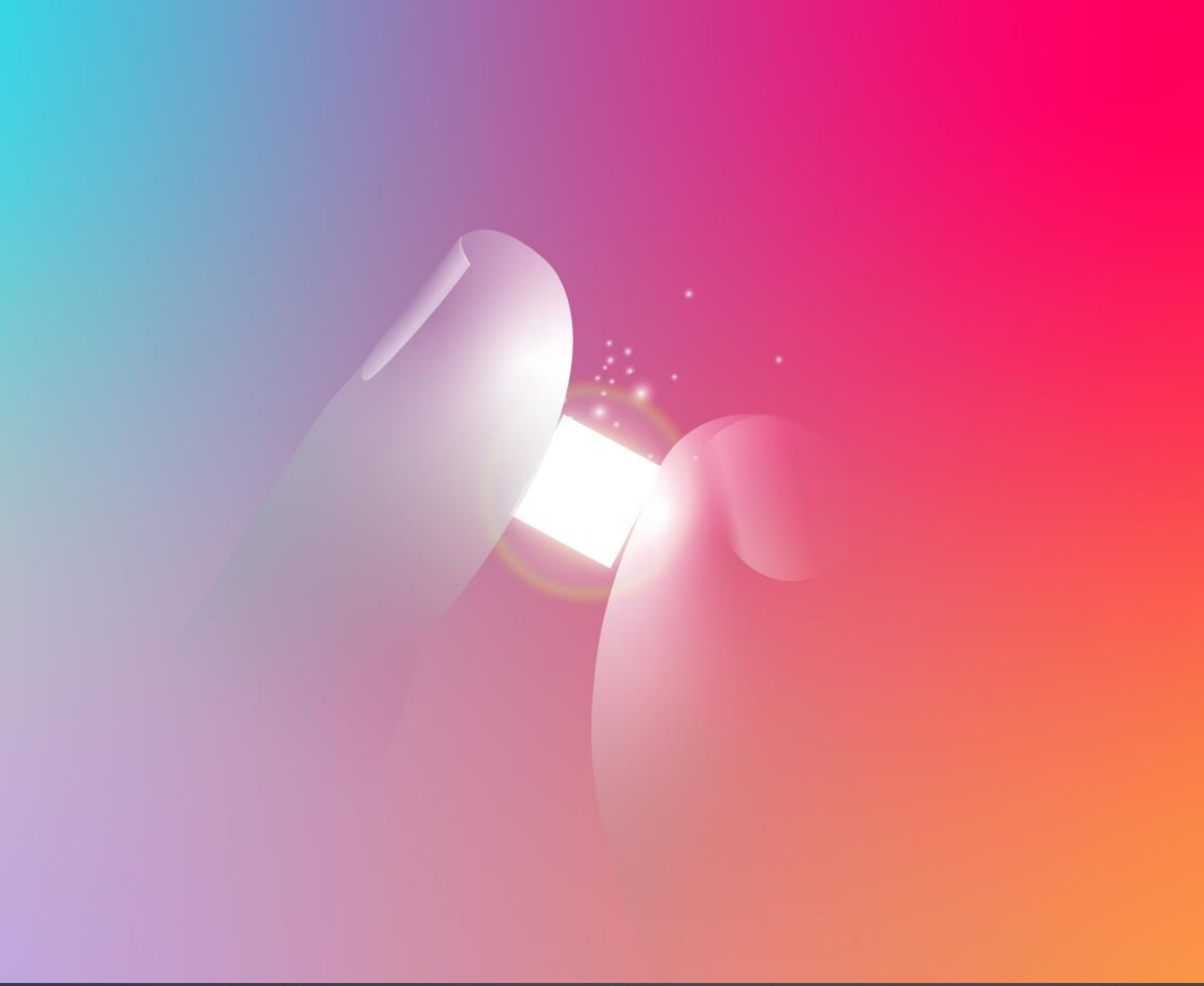

UV-C LEDs and their use in disinfection applications

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Sensing is life

Abstract

UV-C radiation for disinfection applications is used for decades. The major light source in most of these applications is the mercury containing UV-C low-pressure discharge lamp. Compared to this mature technology the UV-C LED is still new and in the introduction phase. LEDs enable new applications which cannot or have not been addressed by conventional lamps before. The radiant power, efficiency and price performance of today's UV-C LEDs show a significant gap to the conventional lamp and a direct replacement of the current technology seems to be very challenging. In this paper we are trying to estimate the point of time by when UV-C LEDs are able to replace conventional UV-C lamps in different applications by performing a total cost of ownership calculation of the UV-C source at several time points in the future based on roadmaps for different performance parameters and considerations of the respective application efficiencies. A comparison of the applications upper air treatment, secondary air treatment, batten fixture surface treatment and municipal water treatment shows that in some applications a lamp replacement by LED is already realistic today. The significant difference of the application efficiency between LED and lamp-based systems lead to an earlier possible adoption of the LED technology than expected from a direct comparison of the performance parameters of the sources itself.

Keywords: UV-C, UV-C LED, low pressure mercury lamp, disinfection, Total Cost of Ownership

1. Introduction and status of the UV-C LED

UV-C LEDs are getting more and more attention over the last years as they can be used as small and compact sources of UV-C radiation for disinfection applications. Especially the mobile applications in the consumer market with a lower requirement on the radiant flux can be addressed with these LED based on the still new AlGaN material system. Compared to blue and white LEDs, which are based on the well-known and developed InGaN system, the UV-C LEDs are still in the introduction phase of the technology.

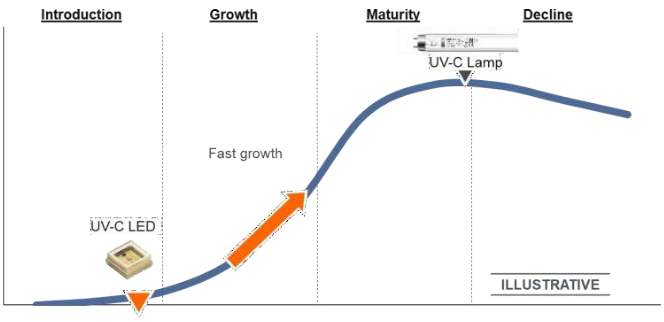


Figure 1. Position of the UV-C LED and UV-C Lamp in the product life cycle

On the other hand, we have the conventional low-pressure mercury discharge lamp, which is a proven technology over decades and reached the state of maturity already. It is very ambitious to target a direct one to one replacement of the UV-C lamps with LEDs today, as a direct comparison of the LED parameters with the lamp show significant differences. Nevertheless, the experience from the introduction of the visible LED in other applications e.g. automotive lighting, general lighting and horticulture lighting show, that the development can accelerate quite fast and the transition from one to the other technology may be faster than expected.

The current ams OSRAM UV-C LED portfolio in Figure 2 gives a good overview of the range of power classes, driving currents and efficiencies. From here we can draw first conclusions in respect to the replacement of the conventional lamps.

Type	Radiant flux [mW]	Peak wavelength [nm]	Emission angle [°]	Voltage [V]	Binning current [mA]	Max. current [mA]	WPE[1)] [%]
Low power Output **SU CULBN1.VC**	4.7	275	120	6.0	30	40	2.6
Mid power Output **SU CULCN1.VC**	13.5	275	120	6	100	150	2.25
Mid power Output **SU CULDN1.VC**	42	275	120	5.7	350	500	2.1
High power Output **SU CZHPF1.VC**[2)]	100	273	120	6.5	250	350	6

1) Wall Plug efficiency
2) New Generation coming soon

Figure 2. ams OSRAM UV-C LED portfolio overview

The radiant flux of UV-C LED today is with 4-100mW much lower compared to conventional UV-C lamps, but in all other LED applications the lamps have not been replaced one to one but by several LEDs arranged in different numbers and shapes. Another parameter where we see a big gap compared to the conventional lamps is the wall plug efficiency (WPE). Here it is not possible to compensate the significant difference to the high efficiency of UV-C lamps easily. Operation of the LED at a significantly lower current density is a common practice in general lighting applications to increase the efficacy. Unfortunately, the gap in efficiency is too big to be bridged by this approach yet.

Lifetime is perceived as one of the big strengths of LED light sources and in many applications. In this respect LEDs are outperforming other conventional light sources by far and allow a completely different system design as the source has not to be replaced over the lifetime of the product. For UV-C LEDs the development is still at the beginning as the new material system is revealing new challenges to solve aging mechanisms already known from the InGaN.

Last not least the difference in price performance of LED compared to conventional lamps is huge. As price performance we define the cost for the radiant flux in the UV-C wavelength range in €/W or $/W. Here we see roughly a factor 100 between a UV-C lamp and LED.

The situation looks quite challenging but there are also advantages of the LED over the conventional lamps. The spectrum of the conventional lamp is determined mainly by the mercury emission line at 254nm which cannot be changed or shifted. The emission wavelength of the LED can be tuned and optimized to the point of highest effectiveness. According to several studies and standards the highest germicidal is effectiveness is at 265nm and this is also target of optimization for the UV-C LEDs. At this wavelength the germicidal effectiveness would be around 15% higher compared to the conventional lamps and the necessary radiant flux in the system to achieve the same disinfection performance can be 15% lower.

The ability to be switched on and off without a negative impact on the lifetime of the LED is another big advantage of the new technology. Conventional lamps have a limited number switching cycles as it impacts the lifetime in a negative way.

The biggest advantage of the LED from the application point of view is the small form factor and the quasi point light source characteristic. The high radiance enables radiation characteristics with a very narrow beam which allows a compact and efficient system design. Here the optical efficiency of the UV-C fixture can be significantly higher compared to lamp-based systems with their low radiance and large emission areas.

Based on the current UV-C LED parameters is seems difficult for the LED to replace a UV-C lamp any time soon but in order to evaluate if and when a replacement seems possible a total cost of ownership (TCO) comparison will be performed for different applications.

2. UV-C LED development and application efficiency

In order to evaluate the realistic and reasonable point of time for a replacement of the conventional source in existing UV-C fixtures by an UV-C LED a TCO evaluation is conducted. In this evaluation we are focusing on the UV-C source only. Other cost factors e.g. fixture housing, size, design are not taken into consideration.

In this evaluation the total cost of ownership TCO is defined as the cost for the initial purchase of the UV-C source as well as the replacement of the source at the end of the lifetime and the energy cost the operation of the UV-C source is causing during the operating life of the fixture. The TCO calculation is based on four major input parameters shown in figure 3 for the LED and the lamp system.

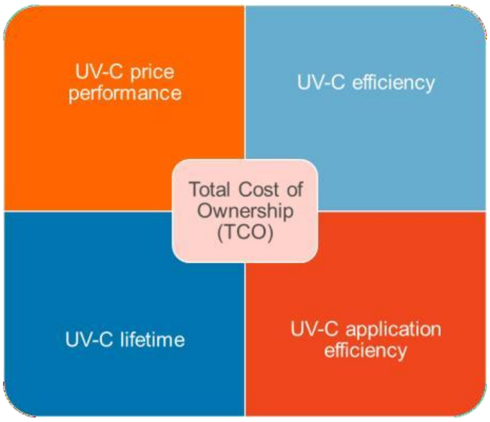


Figure 3. The 4 input parameters for the TCO calculation

For each input parameters we are considering the status today and the development of the parameter over the next year until 2030. These projections into the future are based on inhouse estimations and assumptions as well as inputs from market studies [1]. They are subject to change and cannot be guaranteed.

2.1 PRICE PERFORMANCE DEVELOPMENT

The price performance development in figure 4 is probably the one with the highest attention as the difference seems to be quite big between the UV-C LED and UV-C lamp from today's point of view.

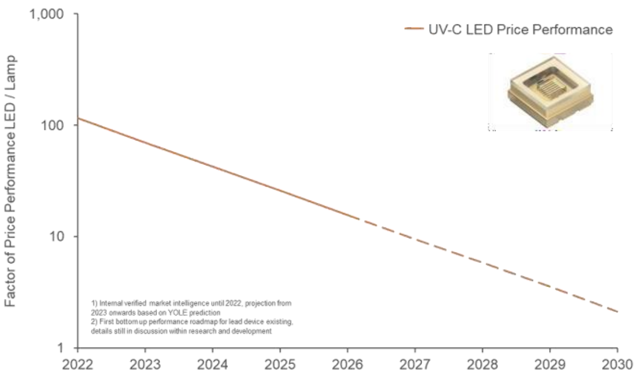


Figure 4. Price Performance roadmap for UV-C sources until 2030

The graph shows the development of the factor of price performance between LED and lamp. The factor determines how many times more expensive a UV-C LED source would be compared to a UV-C lamp in €/W. Since prices are varying quite a lot for different LED and lamp types as well as power classes, an average value has been assumed for this roadmap. Today the factor would be around 100. There are strong indications that the price performance of the UV-C LED is improving significantly over the next year and it will come much closer to the cost of conventional lamp. The most interesting point here is: Do we have to meet the same price performance level as the conventional low-pressure mercury lamp to be competitive and replace the lamp in disinfection applications? The clear answer is NO!

A comparison to other applications where LED is very successfully replacing conventional light sources is showing clearly that it is not necessary to meet the price performance of a conventional lamp to enable the replacement and be successful in an application. The two examples in figure 5 are showing the price performance development for LEDs used in the streetlighting and horticulture lighting applications.

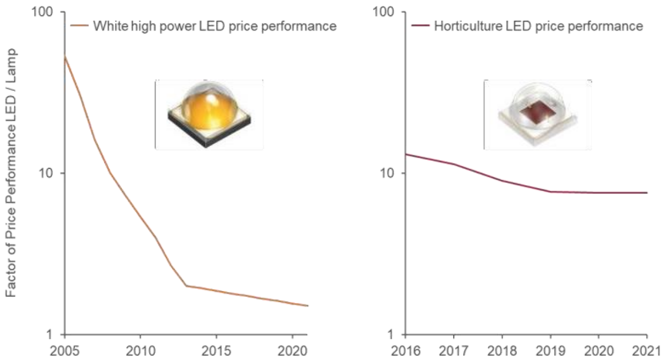


Figure 5. Price performance development for LEDs in streetlighting and horticulture applications

In streetlighting applications, the price for the white high-power LED has reduced significantly over the last years. Even today the LED source is more expensive in €/lm compared to the conventional sources. Nevertheless, LED could be already considered as the state-of-the-art light source for new streetlighting installations.

The same holds true for LED in horticulture lighting applications. Here the difference in price performance of the red LED is significantly larger compared to the white LED in streetlighting. However most new designs are currently done around a LED source and the market for horticulture LEDs is growing constantly.

This shows clearly that price performance is an important factor when designing a system, but there is no need to meet the price performance of the conventional lamp to be successful in the application because it cannot be judged on its own but only in a complete system and a TCO calculation considering all other parameters of an LED design as well.

2.2 EFFICIENCY DEVELOPMENT

A next parameter is the source efficiency in figure 6. Here efficiency of an UV-C lamp is much higher than the efficiency of an UV-C LED. The efficiency has been adjusted and scaled by 15% to the germicidal effectiveness at 265nm [2] as the peak wavelength of LEDs is an assumed to be at 265nm for this evaluation.

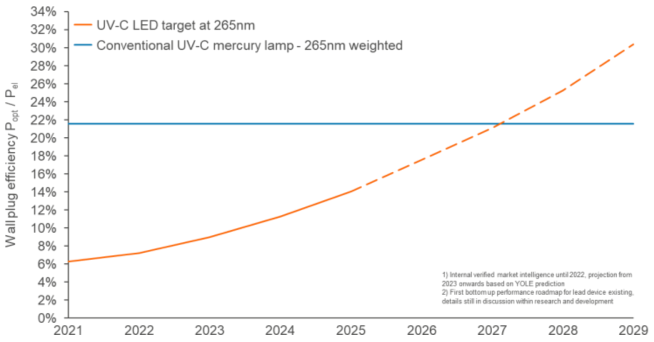


Figure 6. Efficiency roadmap for UV-C sources until 2030

The efficiency development of the conventional UV-C lamp is assumed to be flat as the technology is already mature and there is no improvement is foreseen for the next years. As the UV-C LED is still at the introduction phase and still at an early stage of the technology there is a substantial improvement expected over the next years. There are several points for improvements e.g. the epitaxial layer, the chip design and structure as well as the package design and materials.

2.3 LIFETIME DEVELOPMENT

The improvements on the LED are also considering an enhancement of the lifetime as shown in figure 7. At reasonable operation conditions the lifetime of the LED is already in the range of an average UV-C lamp today and it is expected to improve in the coming years which will impact seriously the UV-C source cost in the TCO calculation as a replacement of the LED source would be very costly. For the conventional UV-C lamps we don't see an improvement of the lifetime.

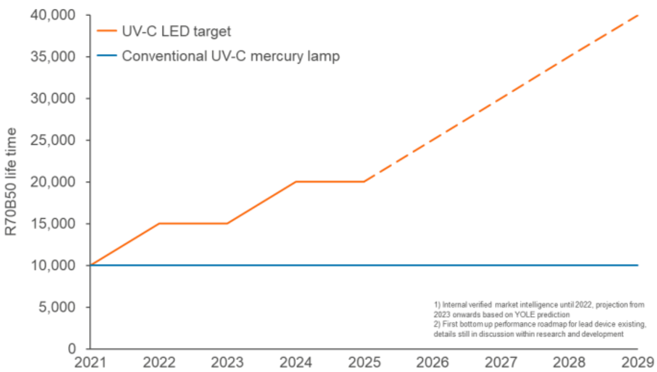


Figure 7. Lifetime development roadmap of UV-C sources over the next years.

An additional feature of the LED system in combination with a UV sensor is the constant output in a closed loop monitoring system. Since LEDs are electronic devices their current sources can be easily controlled by a microcontroller. In case of a drop of radiant flux the UV sensor in the system could measure the deviation and the microcontroller would be able to adjust the current of the LED driver accordingly to keep the targeted irradiance level in the application always at the desired level.

2.4 APPLICATION EFFICIENCY

The last input parameter for the TCO calculation is the application efficiency or system efficiency of the UV-C fixtures in different applications. The four applications shown in figure 8 are used exemplary to show and judge the impact of the application efficiency on the TCO calculation. The values have been derived from product datasheets and internal simulation.

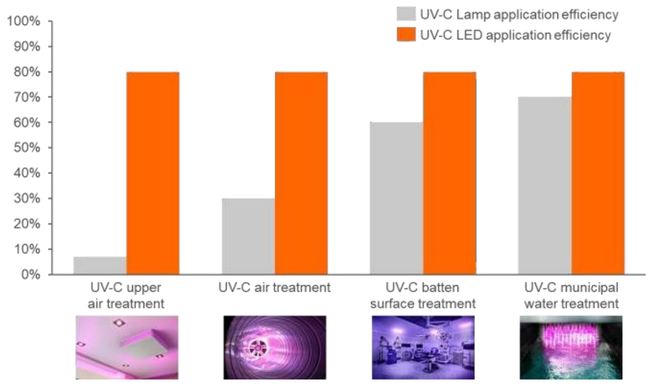


Figure 8. Application efficiency of UV-C disinfection applications for lamp and LED based systems

In the UV-C upper air treatment application the system is generating a very narrow beam of UV-C radiation underneath the ceiling. Due to the requirement of a radiation within less than 10° and the limited size of the fixture the system can be considered as etendue limited and it is very difficult to direct the radiation from the UV-C lamp with optics into the narrow beam. At a given size of the fixture the task can only be achieved by sacrificing a huge amount of radiation as optical losses in the system. The point light source feature of the LED with its high radiance can be collimated in a highly efficient way and is therefore perfectly suited for this kind of application. The huge difference in application efficiency will have an enormous impact on the TCO calculation.

In the UV-C air treatment application the air is treated with UV-C radiation while it is forced through a box by ventilation. If a conventional lamp is used along the length of a fixture, the free distance for the photons to propagate from the source to the walls of the box is quite short. Therefore, the reflectivity of the wall has a big impact on the efficiency of the system. Simulations showed that LED systems with collimated narrow beams may have a 2-3 times higher average irradiance inside the system based on the same optical radiant flux compared to lamp systems.

For surface treatment applications simple UV-C batten fixtures are used. The target here is to direct the radiation uniformly over a surface. This requires basically a hemispherical radiation characteristic from the fixture. If a conventional lamp is used, the omnidirectional radiation must be turned into a hemispherical radiation using reflector systems.

These systems are causing optical losses and reduce the application efficiency of the fixture. UV-C LEDs have an advantage with their intrinsic hemispherical radiation characteristic which helps to reduce the optical losses in the system and provide a higher application efficiency.

The last application in this evaluation is the UV-C municipal drinking water treatment. Here the application efficiency of LED and lamp systems are very similar. The omnidirectional radiation characteristic of the lamp and the large irradiation area has no serious disadvantage in the system design as the water usually flows around the source without any additional optical system. Large scale LED reactors are still rare and internal simulations and estimations are indicating only a small advantage in the application efficiency for the LED based systems due to the small form factor, the radiation characteristic and the flexible arrangement. This may change with new reactor designs around LEDs in the future.

Based on this input data on the UV-C sources, the development over time and assumptions on the system and operation parameters for each application the TCO is evaluation for the next years until 2030 with the focus on the UV-C source only. Figure 9 shows an example.

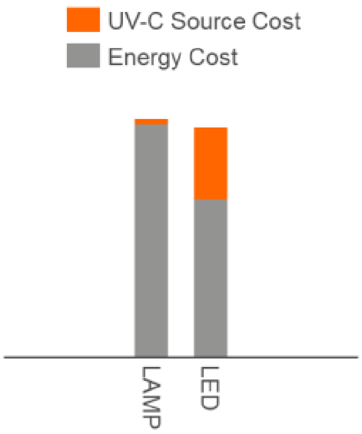


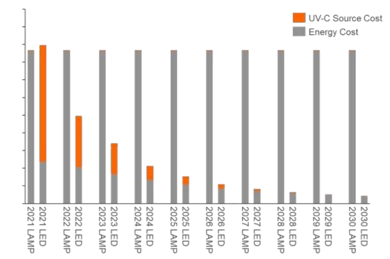
Figure 9. Example of a TCO comparison of a lamp and LED based system

The total cost consists of the UV-C source cost part which is considering the initial purchase of the source as well as a replacement of during the operating life of the fixture of 5 years if the source reached the end of its lifetime. The second part is considering the accumulated cost for the energy used by the UV-C source in the system over the operating life. Together they represent the TCO for the UV-C source in a lamp based and a LED based system.

3. Total cost of ownership (TCO) evaluation

3.1 TCO EVALUATION RESULTS FOR THE UV-C UPPER AIR TREATMENT APPLICATION

As shown earlier the huge difference in optical efficiency between the lamp and the LED based system has an enormous impact on the cost composition in the TCO calculation as shown in figure 10.



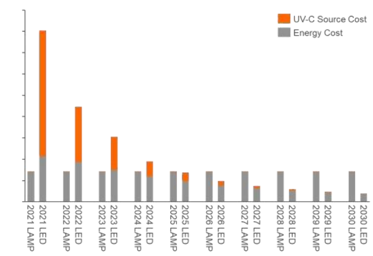
Parameter	Unit	UV-C Lamp	UV-C LED
System radiant flux @ 265nm	W	0,4	0,4
System radiant flux @ 254nm	W	0,48	
System optical efficiency	%	7%	80%
Source radiant flux	W	7,4	changing
Energy Cost	€/kWh	0,20	
Operating hours per day	h	8	

Figure 10. TCO evaluation for the UV-C upper air treatment application over the next years

The UV-C source cost for the conventional lamp system is extremely small compared to the large part of the energy cost. This is caused due to the low optical efficiency in the system. In the LED based system, the energy cost has a smaller share and the UV-C source cost is larger. Here the advantage of the high radiance or point light source feature in the etendue limited system is clearly visible but also the high price for the UV-C radiation created from LED can be recognized. The evaluation shows, that a replacement of the conventional UV-C lamp with LEDs may be possible already today and the savings of a LED based system over a lamp-based solution will increase in the next years.

3.2 TCO EVALUATION RESULTS FOR THE UV-C AIR TREATMENT APPLICATION

In the UV-C air treatment application the difference in the application efficiency gets smaller between the UV-C technologies. Therefore, the energy cost of the lamp-based fixture and the LED based version is quite similar.



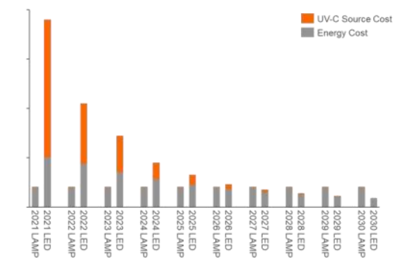
Parameter	Unit	UV-C Lamp	UV-C LED
System radiant flux @ 265nm	W	18,4	18,4
System radiant flux @ 254nm	W	21,6	
System optical efficiency	%	30%	80%
Source radiant flux	W	240	changing
Energy Cost	€/kWh	0,20	
Operating hours per day	h	8	

Figure 11. TCO evaluation for the UV-C air treatment application over the next years

Figure 11 shows that in the next years the big difference in TCO is caused by the UV-C source cost. Here the LED has a higher price which leads to a higher TCO. But already in 2025, the improved efficiency of LEDs, according to the roadmap, and the reduced cost for the source show a small benefit of the LED based system and suggest the potential replacement of the lamp.

3.3 TCO evaluation results for the UV-C batten fixture surface treatment application

With a further reduced difference of the application efficiencies between the lamp and the LED based system the gap in performance of the input parameters are having a more direct impact on the TCO as shown in figure 12.



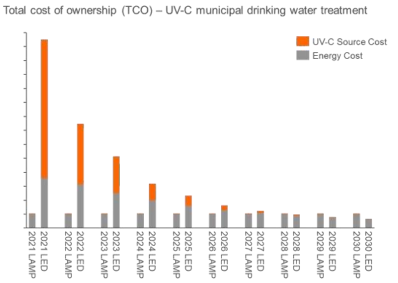
Parameter	Unit	UV-C Lamp	UV-C LED
System radiant flux @ 265nm	W	8,7	8,7
System radiant flux @ 254nm	W	10,2	
System optical efficiency	%	60%	80%
Source radiant flux	W	17,0	changing
Energy Cost	€/kWh	0,20	
Operating hours per day	h	8	

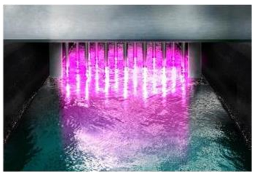
Figure 12. TCO evaluation for the UV-C batten fixture surface application over the next years

The electrical efficiency of the fixtures is following more directly the UV-C source efficiencies. Therefore, the difference shown in the efficiency roadmap between lamp and LED is dominating the course of the graph and suggests a replacement of the conventional lamp by a LED system around 2026 to 2027. It should be noted that the cost of the UV- C LED source alone in these years is still significantly higher than the UV-C lamp cost but due to the combination of efficiency, lifetime and application efficiency the TCO is still on par.

3.4 TCO evaluation results for the UV-C municipal drinking water treatment

The biggest challenge for an UV-C lamp replacement may be the large-scale water treatment application. Here the difference in application efficiency is very small and therefore the direct gap in the UV-C source parameters e.g. price performance, efficiency and lifetime are dominating the calculation.





Parameter	Unit	UV-C Lamp	UV-C LED
System radiant flux @ 265nm	W	410	410
System radiant flux @ 254nm	W	483	
System optical efficiency	%	70%	80%
Source radiant flux	W	690	changing
Energy Cost	€/kWh	0,20	
Operating hours per day	h	24	

Figure 13. TCO evaluation for the UV-C municipal drinking water treatment application over the next years

According to the calculation results in figure 13, a lamp replacement in this application may be reasonable around the years 2027 to 2028. This may change with new reactor designs coming up which are focusing and make use of the LED properties but the difference in application efficiency today is quite small.

3.5 Combination of the replacement roadmaps the UV-C lamp and system market

Based on the assessment of the different applications before it seems that regarding the replacement of the UV-C lamp with LEDs three different groups could be formed.

Big application advantage: This group covers applications like upper air treatment with a big difference between the application efficiency of a lamp-based system and a LED based system. This would also apply to other application requirements like narrow radiation characteristics, frequent switching or an environment with shock or vibration.

Medium application advantage: This group covers applications like air treatment or surface treatment with a medium difference in application efficiency. It could also apply to systems with other hemispherical radiation characteristics, uniform irradiation of areas or a long-time irradiation at low irradiance.

Small application advantage: This group covers applications like large scale water treatment where no or little difference in the application efficiency can be assumed. This would also include applications with omnidirectional radiation.

As a next step the total UV-C lamp and system market which could be targeted for a lamp replacement by UV-C LED has been estimated as well as the market size of the sub applications like air, surface and water treatment. Each sub application has been grouped according to the three application advantage groups and the point of time by when a lamp replacement seems reasonable based on the TCO calculation has been determined. The transition can be seen in figure 14.

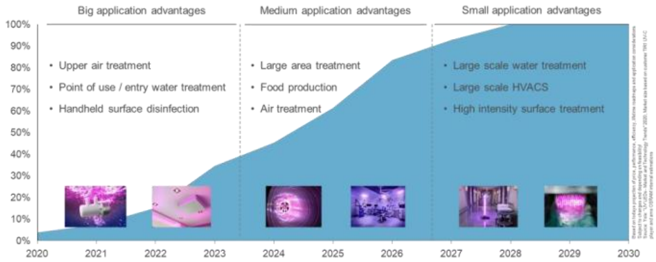


Figure 14. LED penetration of the traditional UV-C lighting lamp and system market over the next years

According to this evaluation 50% of the conventional UV-C lamp application market could be addressed with UV-C LED by 2025.

4. Conclusions and outlook

The differences in the key parameters between UV-C lamps and UV-C LED today will get significantly smaller within the next years due to continuous improvement of the LED price performance, efficiency and lifetime. It has been shown that a direct comparison of the key parameters between the different technology alone does not allow a realistic assessment on the timing for the replacement as the application efficiency and system design has a substantial impact and must be considered in the evaluation as well. The comparison of the different examples show clearly that LED based designs can have a significant higher application and system efficiency due to the unique features and characteristics of the LED. A combination with a UV sensor provides additional benefits and can extend the lifetime of the LED source as well as the complete system significantly. The design of the fixture for the different application must be adapted to the new UV-C source technology in order to harvest the full benefits. The replacement of UV-C lamps has already started, and it is continuing over the coming years by addressing more and more applications. By the 2025 the UV-C LED should be able to address already 50% of the conventional UV-C lighting lamp and system market.

5. Acknowledgement

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6. References

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