D4.1 Report on artificial lighting solutions

Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems

iNSPiRe

SEVENTH FRAMEWORK PROGRAMME

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Acronyms

CFL	Compact Fluorescent Lamp
CRI	Colour Rendering Index
DOE	Department of Energy (USA)
GLS	General Lighting System
HID	High Intensity Discharge lamp
IR	Infrared
klm	Kilolumen
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LED	Light Emitting Diode
LFL	Linear Fluorescent Lamp
lm	Lumen
LOR	Light Output Ratio
NIR	Near Infrared
OLED	Organic Light Emitting Diode
pc	Phosphor Converted
R_a	Colour Rendering Index
RGB	Red Green Blue
R_i	specific colour rendering index (Munsell colours)
SSL	Solid State Lighting
UV	Ultra violet
W	Watt

1 Introduction

As part of the research project iNSPiRe this report will give a detailed look into the characteristics and properties of common light sources and luminaires. For detailed definition of many specific definitions it is referred to (Tetri et al. 2010).

This report will describe contemporary lighting systems and will forecast future evolutions based on different references.

The report compares halogen, compact fluorescent – CFL - and light emitting diodes – LED - solutions, both lamps and luminaires.

It will also provide lifetime costs and life cycle analysis. The presented systems will be compared and evaluated. Accordingly, recommendations of lighting systems to be used for both residential and office application will be given.

2 Definition, Evolutions and Forecasts

2.1 Lighting System

A lighting system consists of three components:

- Lamp: emitting light source
- Controller: connection between voltage supply and light source, (transforming voltage, starting device and probably integrated in control system)
- Luminaire: apparatus, which distributes filters or transforms the light, which is emitted by the lamp (reflector, foils, covering glass, etc.). The luminaire integrates the plug-in slot for the lamp, which is called socket.

The efficiency of the lighting systems consists of

- Efficacy of the lamp: ratio of the light output by the lamp over the electric energy input into the lamp [lm/W]
- Efficiency of the controller: power factor and stand-by
- Efficiency of the luminaire: ratio of the light output by the luminaire over the light output by the lamp [called LOR = Light Output Ratio, given in %]
- Room utilization factor (i.e. reflected light, depending on reflectivity, geometry, etc.).

2.2 Light sources

IEA Annex 45 (Tetri et al. 2010) final report was delivered in 2010. This report might be used as a very detailed description of light sources and equipment but since especially solid state lighting is intensely emerging and will undergo further developing, then efficiency data mentioned back (Figure 2) should be checked with modern data.

The different light source technologies are based on 3 main physical principles (Tetri et al. 2010, p.93-118):

1. Thermal radiation (Black Body Emitters)

- Incandescent lamps (used for decades, will be banned from market).
- Tungsten Halogen lamps

2. Recombination in discharge lamps (Fluorescent lamps)

- Fluorescent tubes (linear fluorescent lamps LFL)
- Compact fluorescent lamps CFL
- High intensity discharge lamps HID
- Mercury lamps (incl. halides)
- High pressured sodium

3. Solid state lighting (Semiconductors)

- LED (Light Emitting Diode)

  Phosphor converter (pc): The semiconductor emits radiation in blue or UV, which is then transformed in visible wavelength, result in 'white'. Color mixed LED work without phosphors; they are generally slightly more efficient, because losses caused by phosphors do not exist.

- OLED (Organic Light Emitting Diode)

The semiconductor consists of organic compounds.

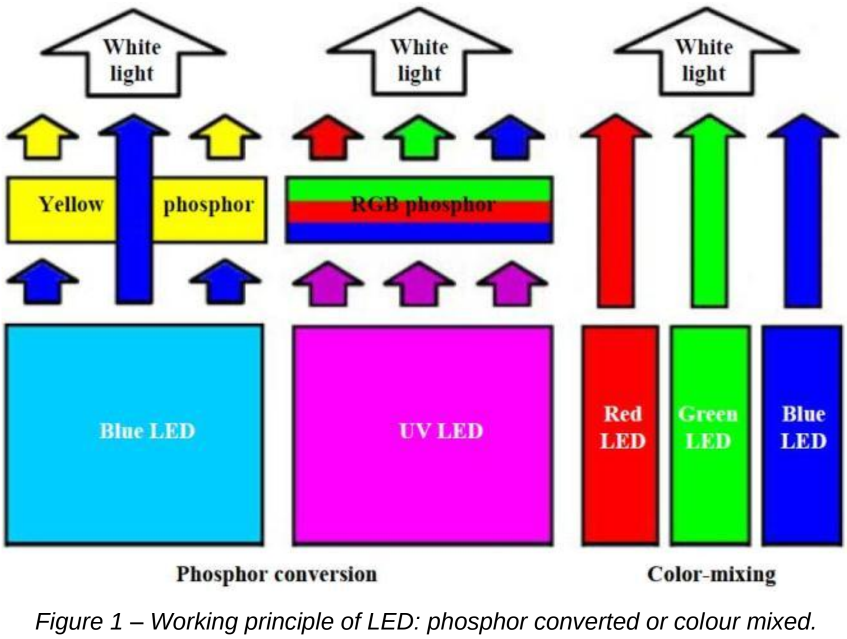


Figure 1 – Working principle of LED: phosphor converted or colour mixed.

In 2010, data about the characteristics of these systems was collected. Especially LED's development should be considered for any new luminaire development.

Lamp type	Characteristics							
	Luminous efficacy (lm/W)	Lamp life h	Dimming control	Re-strike time	CRI	Cost of installation	Cost of operation	Applications
GLS	5-15	1000	excellent	prompt	very good	low	very high	general lighting
Tungsten halogen	12-35	2000-4000	excellent	prompt	very good	low	high	general lighting
Mercury vapour	40-60	12000	not possible	2-5 min	poor to good	moderate	moderate	outdoor lighting
CFL	40-65	6000-12000	with special lamps	prompt	good	low	low	general lighting
Fluorescent lamp	50-100	10000-16000	good	prompt	good	low	low	general lighting
Induction lamp	60-80	60000-100000	not possible	prompt	good	high	low	places where access for maintenance is difficult
Metal halide	50-100	6000-12000	possible but not practical	5-10 min	good	high	low	shopping malls, commercial buildings
High pressure sodium (standard)	80-100	12000-16000	possible but not practical	2-5 min	fair	high	low	Outdoor, streets lighting, warehouse
High pressure sodium (colour improved)	40-60	6000-10000	possible but not practical	2-6 min	good	high	low	outdoor, commercial interior lighting
LEDs	20-120	20000-100000	excellent	prompt	good	high	low	all in near future

Figure 2 – Description of different light sources, their efficacy, their life time etc. This data was collected and finally released in 2010 (Tetri et al. 2010, p.96).

Following four different technologies are compared for efficiency in investment and light output.

Light Source	Type	Phi operating	Power	Price	lm/W	€/klm
Flourosecent Tube	FQ 80W 830 HO	7000 lm	80 W	2,5 €	88 lm/W	0,4 €/klm
Metal halogenid discharge	HCI-T 150W 830	15500 lm	150 W	12 €	103 lm/W	0,8 €/klm
Halogen	Halostar Eco IRC 50W	1250 lm	50 W	2,5 €	25 lm/W	2,0 €/klm
HighPower-LED	Luxeon M 830	900 lm	8 W	3,5 €	113 lm/W	3,9 €/klm

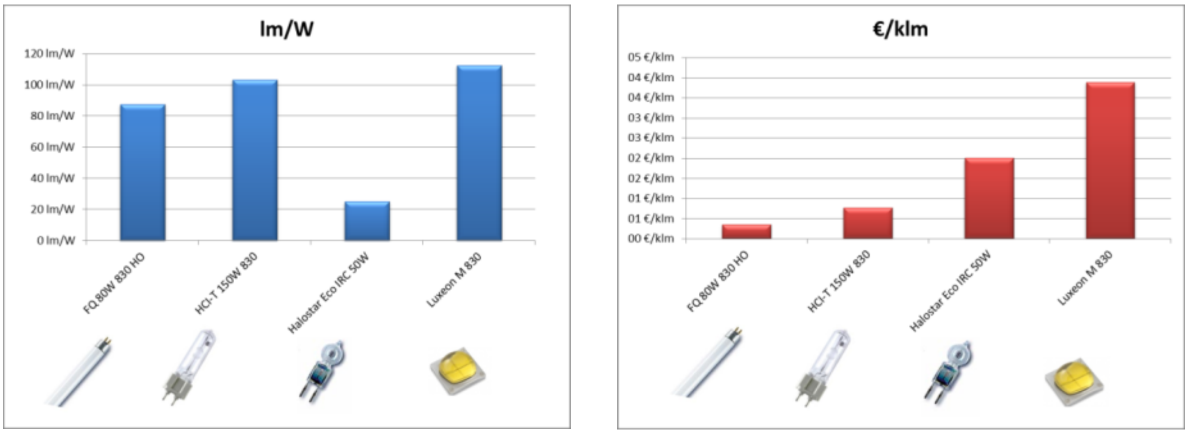


Figure 3 – current state of efficiency (energy lm/W and investment €/klm). (Internal market analysis BLL, 2012)

2.3 Incandescent ban

The ban of energy inefficient light sources is progressing in the European Union, as well as in the USA and Asia. In the EU, most types of incandescent and halogen light sources will be phased out until 2016 because of their bad energy efficiency.

The alternative light sources (lamps) for all retrofit applications will be CFL- and LED bulbs (see following chapter 2.4). Both light sources are rated A by the EEI- energy efficient index, although a LED is more efficient already now, in 2013, and will become even more efficient in the near future (chapter 2.5). In order to consider the increasing efficiency of LEDs and CFLs, the EU will modify the energy label starting End of 2013. Two new categories will be implemented: A+ and A++.

2.4 Definition of 'lighting retrofit' vs. 'luminaire replacement'?

Talking about lighting retrofit is not completely precise: two possible interventions exist. In this report, the lamp replacement option (see paragraph 2.4.1) will be the further considered one.

2.4.1 Keeping old luminaires and replacing lamps

All lamp producers provide today LED lamp, which are brought into shape to fit into common sockets. All these components are called hereafter led bulbs, or LED retrofit bulbs. As consumers are very likely to keep their luminaire, this market is estimated to be the largest near term market for Solid State Lighting (SSL, e.g. LEDs).

Figure 4 – Led package is integrated in a structure to fit into socket E27.

- LED bulb, which looks exactly the same as an incandescent bulb, already integrated driver, etc. They are available between ~5€ to 100€ per bulb, which is advertised with different colour rendering, higher lifetime, higher luminous flux, etc.

Figure 5 – Philips LED retrofit bulb with an arbitrary product for E27 socket

- LED tubes, which look like common fluorescent tubes.

Figure 6 – LED tube for fluorescent retrofit for T5/T8 socket

- Any other socket replacement

Figure 7 – IKEA LED retrofit for GU4 socket

2.4.2 Replacement of lighting system (luminaire, lamp, controller)

In this case, no old components are kept. As described in chapter 2.1 the efficiency of a lighting system is the integral efficiency of lamp together with geometry and surfaces of the reflector and covering glass (=the luminaire). Replacing the single lamp, leaves the second lighting efficiency contributor unconsidered, this leads in the worst case to malfunction of the luminaire (light distribution, thermal problems, etc.).

Luminaire design must be based on the geometry of the lamp together with the light distribution requirements (Figure 8 and Figure 9).

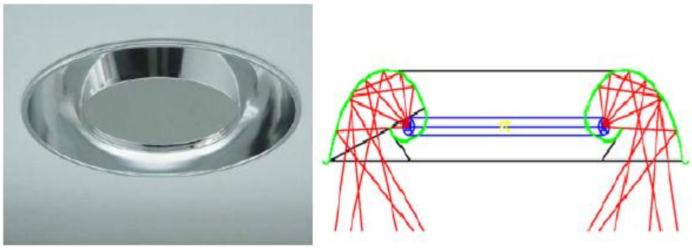


Figure 8 – Luminaire design based on lamp geometry (circular fluorescent tube) and targeted light distribution. For highest efficiency is the sum of both, not the single component.

The small dimensions of LED give today the possibilities to design very elegant and small luminaires which are indeed more efficient than retrofitted luminaires (retrofitted luminaires are the ones with replaced lamps).

Figure 9 – LED luminaires, developed by Bartenbach

Well-presentable examples for the above described approaches are lay-in troffers (Figure 10; a trough-shaped reflector holding one or more fluorescent lamps, for integration in suspended ceilings). The prevalent question remains then: should we replace the fluorescent tubes by LED tubes or the whole troffer, which one is more efficient?

Figure 10 - Lithonia Lighting- troffer for fluorescent tubes

2.5 Efficiency evolution

2.5.1 Retrofit bulbs

While incandescent lamps will be phasing out, CFL and LED bulbs will be the alternatives for retrofitting activities. Still available halogen elements won't be considered as their lamp efficacy is low compared to CFL and LED bulbs. In 2013 CFL bulbs reach up to 66 lm/W while LED bulbs provide in maximum 80 lm/W. This bulb pay the price for high efficiency with poor colour rendering. LED bulbs are generally not able to reach 120lm/W as single LED packages do. .

Looking at the efficiency development of different light sources in Figure 11, LEDs show the highest potential, while all other incumbent lamps' efficacy is not expected to undergo major improvements as this technology is already mature, except industry efforts are successful.

Linear Fluorescent tubes are reaching efficiencies up to 120lm/W, with as counterpart a reduced spectral quality (Colour Rendering). Same for HID (High Intensity Discharge lamps), which reach already 120lm/W with poor spectral quality. LED bulbs are today at approx. 50lm/W, with some superior samples (Philips) available at 90-100lm/W. OLEDs are obviously still looking for their unique selling point (UPS), regarding efficiency the last two years brought a significant improvement. LG offers a panel at 60lm/W. (for further details see (Broderick 2012, p.38-41).

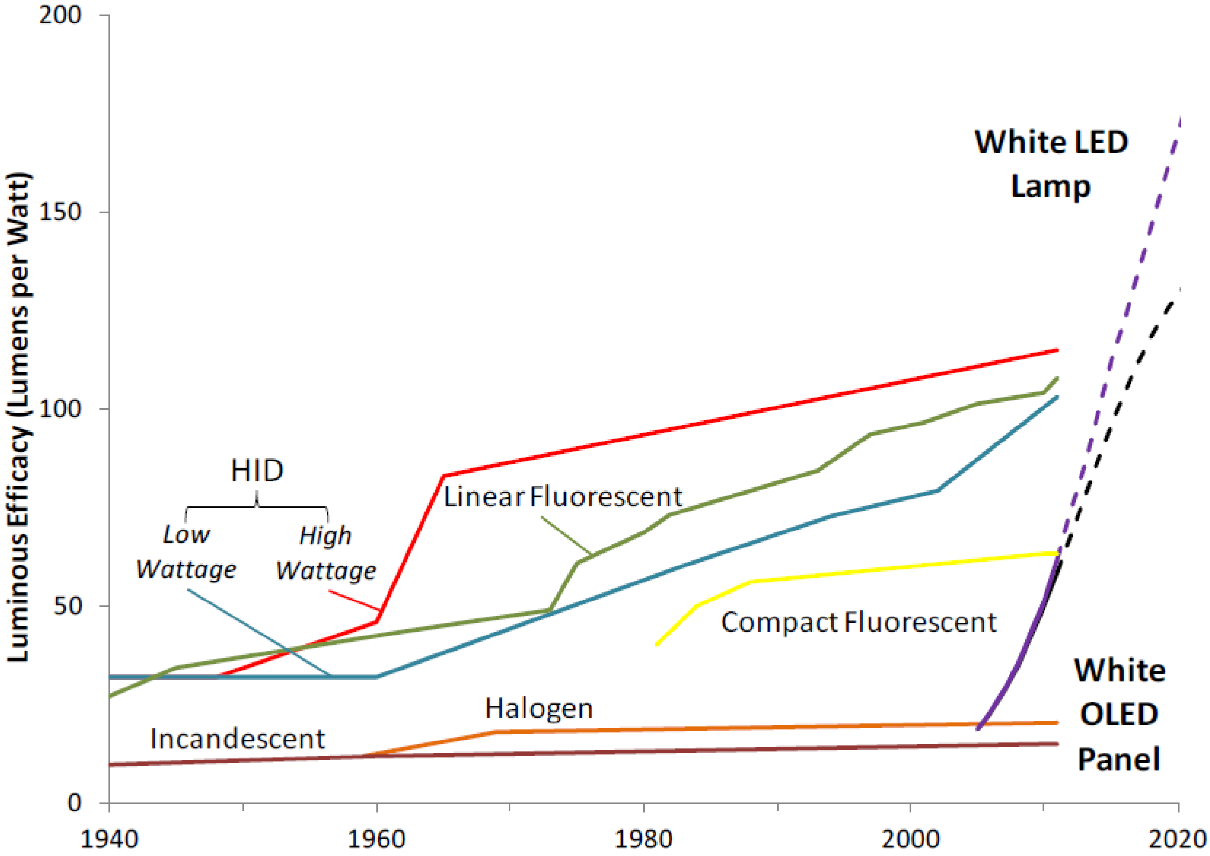


Figure 11 - SSL- Historical and Predicted Efficacy of Light Sources; Solid State Lighting (SLL) like LED offers the highest potential for advancing. Note: Efficacies for HID, fluorescent, and LED sources include driver or ballast losses. (Broderick 2012, p. 38)

As already mentioned, Figure 11 shows efficacy for retrofit bulbs, which include drivers etc. The total potential of LED is shown in Figure 12, where the LED itself (LED package) is evaluated. In Phosphor converted LED pc-led the semiconductor emits radiation in UV or blue. This radiation is then transformed by a phosphor layer (see Figure 1) into visible wavelength. This process is generally more efficient for cool white LED than for warm-white ones. Warm white LEDs, with a colour temperature lower than 3000K, are the closest equivalent to an incandescent light source. According to the prognosis of Broderick,Ttis type of pc-LED will achieve about 160 lm/W in 2016 (Figure 12) while Pc-LED cool will achieve 180lm/W. Colour mixed LED will outperform PC-LED significantly and will reach soon 200lm/W. (Haitz' law is estimating this development, comparable to Moore's law: double performance within 18-24month, which was proven valid through decades.)

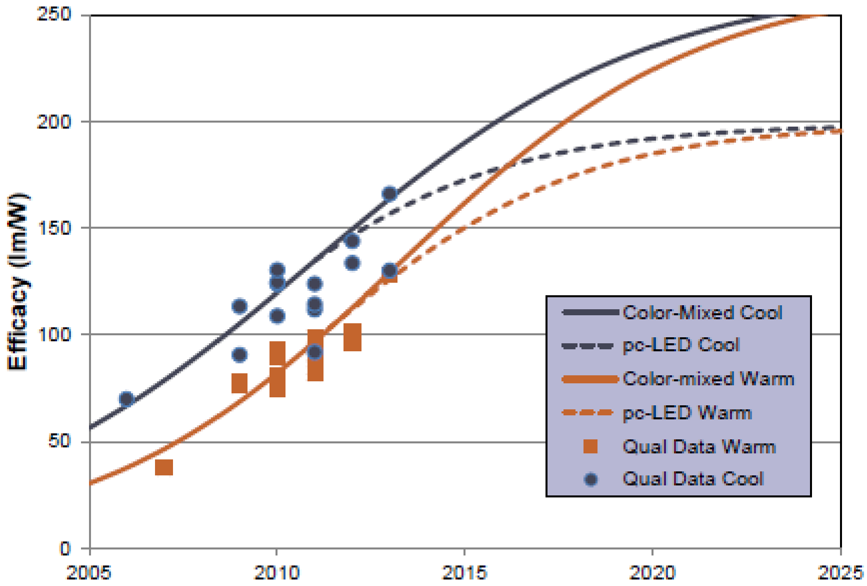


Figure 12 - Efficiency prognosis of LED packages until 2025 (Broderick 2013, p. 42)*; pc...Phosphor converted (for short explanation see chapter 2.2 and Figure 1); Qual Data Warm / Cool are measured data.*

2.6 Price prognosis

While the efficacy of LED packages will rise in the upcoming years, their price will coincidently decrease. The US department of energy (DOE) estimates the price of LED packages to drop in 2020 below the equivalent of 10% of the price in 2010 (Figure 13).

The McKinsey lighting report (Baumgartner, Wunderlich, and Jaunich 2012) predicts an annual price decrease between -14% and -24% (Figure 13).

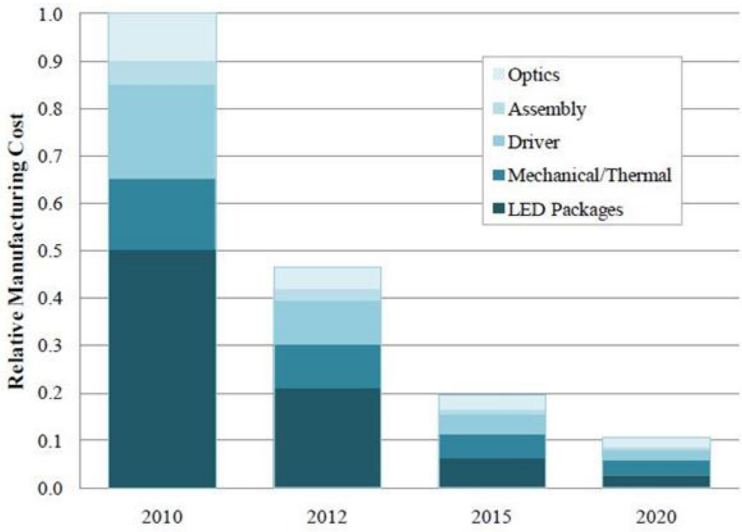


Figure 13 - LED package price forecast [source: DOE, Manufacturing Roundtable Consensus (Indoor Downlights)]

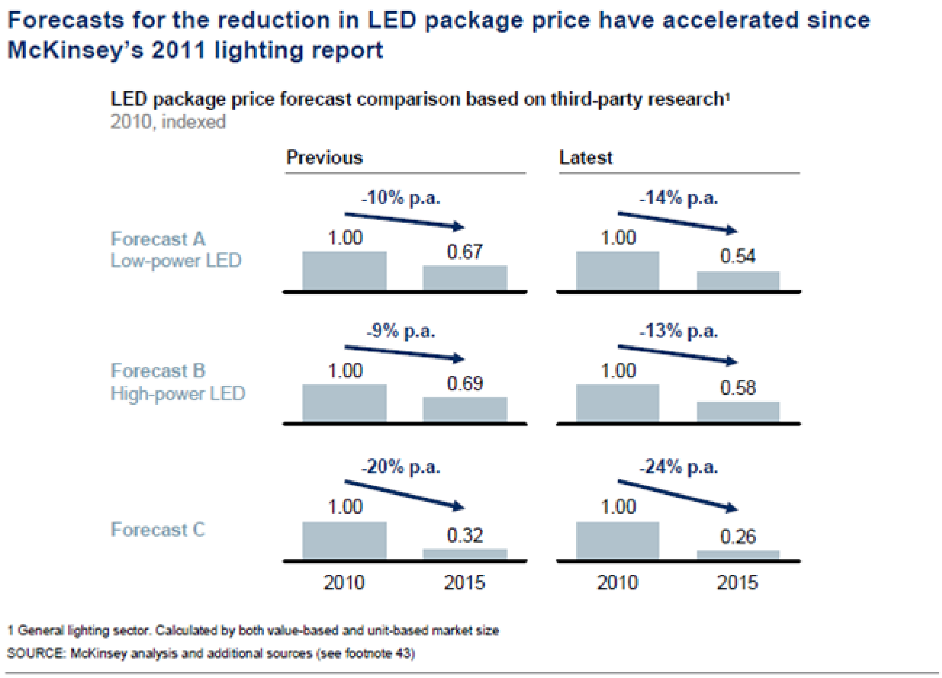


Figure 14 - LED package price forecast (Baumgartner et al. 2012, p.18)

Investment in LED lighting solutions is today up to five times higher than standard solutions, but payback time is – depending on application –short. This depends also very much on the prices for electricity (following chapter 2.7)

2.7 Evolution of Electricity Prices

In order to properly calculate the costs for energy consumption and production of the different light sources, forecasts of electricity prices are considered. The average electrical price evolution in EU-28 during the last 5 years shows a yearly inflation rate of 4.5%.

Assuming this yearly inflation rate and the actual price of 2013, >0.27€/kWh are forecasted for EU-28 households resp. >0.16€/kWh for industrial consumers in 2020.

Electricity prices vary a lot inside Europe, this is due to different VAT levels, different funding of renewables and growth rate of renewables. This is beyond the scope of this report.

This4.5% yearly inflation rate of the electrical price will be further considered in this report.

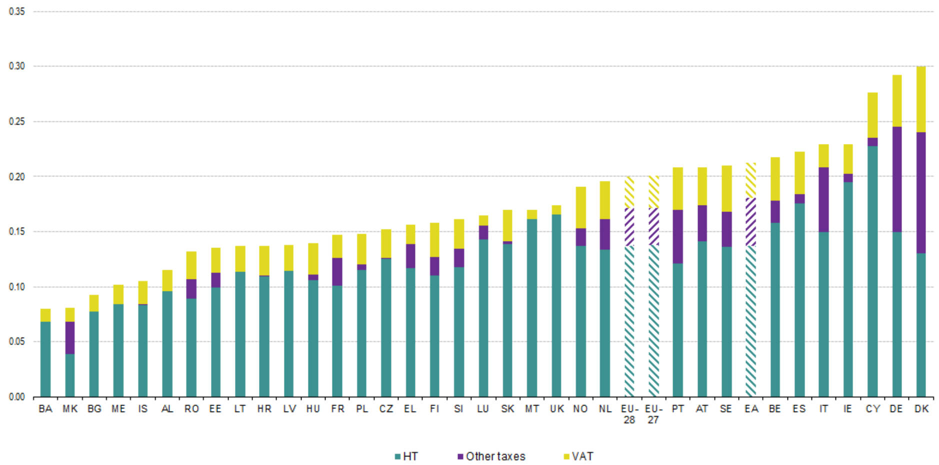
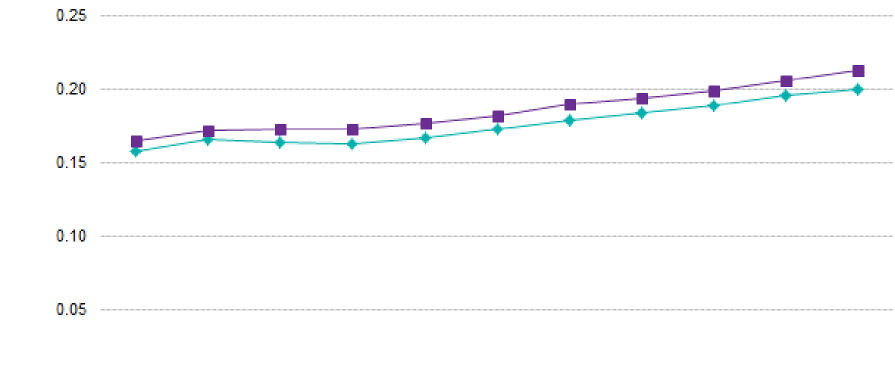
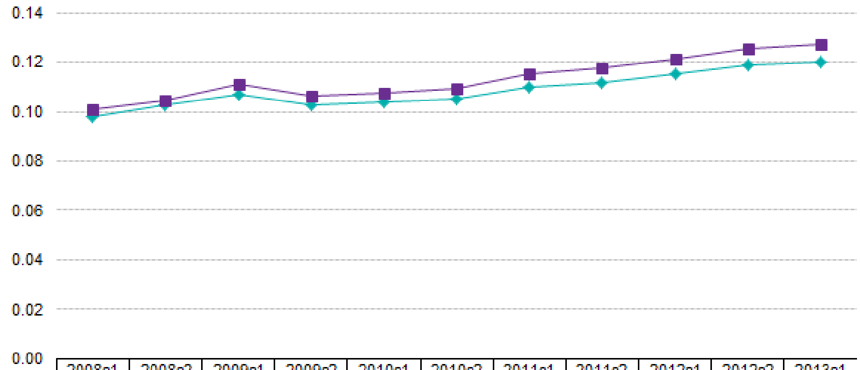


Figure 15 – Electricity prices differ through Europe due to political ideas (VAT, funding of renewables, etc.)



	2008s1	2008s2	2009s1	2009s2	2010s1	2010s2	2011s1	2011s2	2012s1	2012s2	2013s1
EU-28	0.158	0.166	0.164	0.163	0.167	0.173	0.179	0.184	0.189	0.196	0.200
EA	0.165	0.172	0.173	0.173	0.177	0.182	0.189	0.194	0.199	0.206	0.213

Figure 16 - Evolution of EU-27 and EA electricity prices for household consumers, EA … Euro Area (Eurostat 2013)



	2008s1	2008s2	2009s1	2009s2	2010s1	2010s2	2011s1	2011s2	2012s1	2012s2	2013s1
EU-28	0.098	0.103	0.107	0.103	0.104	0.105	0.110	0.112	0.115	0.119	0.120
EA	0.101	0.104	0.111	0.107	0.108	0.109	0.116	0.118	0.122	0.126	0.127

Figure 17 - Evolution of EU-27 and EA electricity prices for industrial consumers, EA … Euro Area (Eurostat 2013)

2.8 Operating hours

The calculation of the energy consumption, and hence costs of the different light sources is based on data about the daily operating hours in residential use. Two independent surveys, one made in California in 2009 and one in the whole US made in 2002, confirm that the average daily operating hours of all sockets in residential use is approx. 2 hours per day (Table 1). All calculations in this report assume that the daily operating hours in European households are similar. The average daily operating hours will be defined as 2 hours.

Table 1 - daily lighting use by room in U.S Households (Bickel, Swope, and Lauf 2010)

	Hours of Use Per Day in U.S. 2002 (All sockets)
Overall	1.9
Kitchen	3
Dining Room	2.5
Living/Family Room	2.2
Bathroom	1.8
Bedroom	1.1
Hall	1.5

In office application operating hours are often guessed to be around 2500h/yr, which gives 10 hours per working day for badly day lit offices. Lighting community defines target values of daylight autonomy of >>70%. This ratio should minimize the operating hours to < 750h/year for offices (equivalent to 3h/working day). So, the range of operating hours in office application is very broad, depending on the daylight availability.

2.9 Life Cycle Analysis

The U.S. Department of Energy report on the "Life Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products" (Building Technologies Office 2013; Tunge et al. 2013) shows in Figure 18 the impact of CFL and LED bulbs in 2012 as well as LEDs in 2017 in relation to incandescent lamps. The 2012 LED bulb has already fewer impacts on the environmental categories than the other lighting solutions except for one category, where the fact that LED needs a heat sink, usually made of Aluminium, causes a slightly higher impact on 'hazardous waste landfill' than for the CFL. But regarding the present rise of LEDs energy efficiency, more energy can be transformed into light, not heat. Therefore the heat sink of future LED products can be smaller and the Impact on the hazardous landfill will shrink.

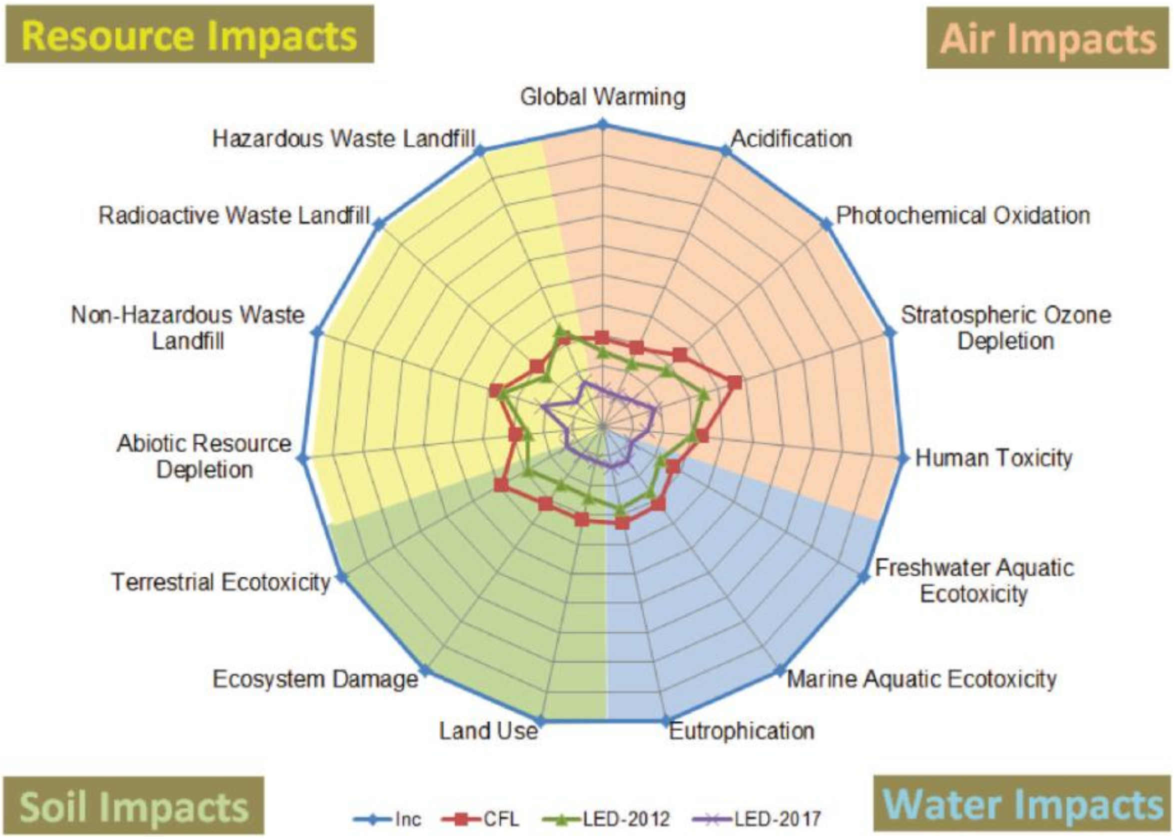


Figure 18 - life cycle assessment impacts of the lamps analysed relative to incandescent (Building Technologies Office 2013)

Improvements in the manufacturing process and higher efficiency will result in a smaller environmental footprint of future LEDs. The DOE's forecast reveals that the consumed primary energy during the life cycle of an LED bulb in the year 2015 will represent 40-50% of its primary energy in 2011 (Figure 19).

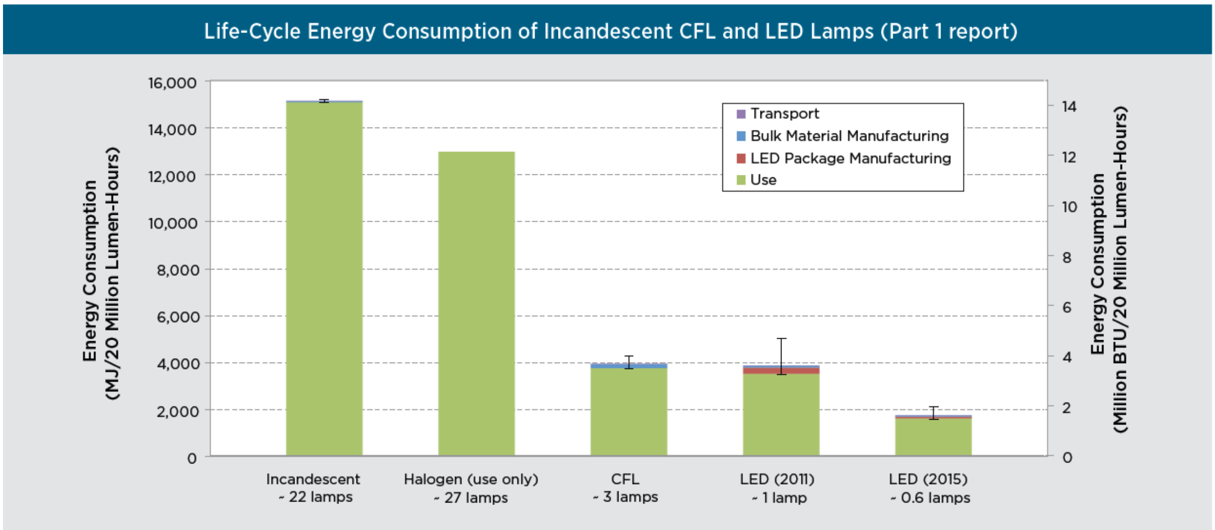


Figure 19 - life cycle assessment primary energy for lamps (Building Technologies Office 2013)

2.10 Market prognosis

Today's global market distribution for different applications is shown in Figure 20. Residential consumers are focusing on incandescent, commercial clients are installing mainly fluorescent lamps.

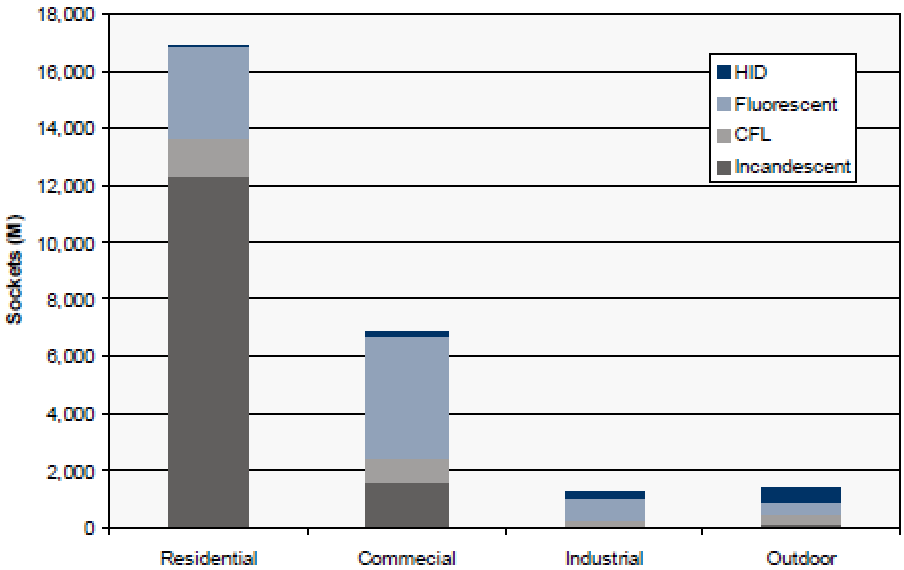


Figure 20 – Global lamp installations by sector and technology 2012 (Broderick 2013, p.4)

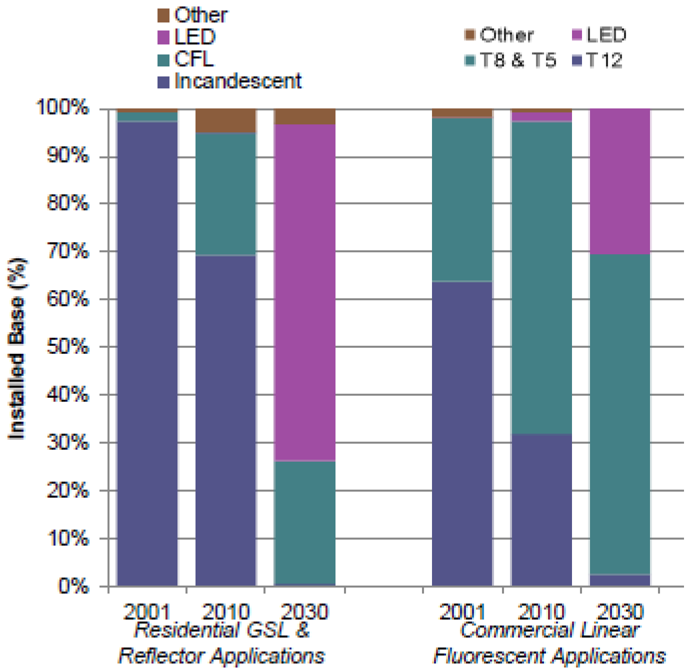


Figure 21 – prognosis for the US market (Broderick 2013, p. 5)

The before described forecasts for efficiencies have been collected and fed into the market prognosis by Broderick 2013. The results show a significant long term impact of LED in the lighting market. This is mainly attributed to the estimated progress in lamp efficiency. Lighting systems will then be designed to reach 200lm/W, compared to 50-100lm/W today.

2.11 SSL - Barriers to Adoption

Broderick 2013 describes the barriers to adoption in three categories:

1. Lifetime:

   Lifetimes of Solid State Lighting (LED, OLED) announced by manufacturers are extremely high, but lifetime of a whole luminaire in reality is quite unknown. Failure modes of Chip, package and luminaire are still barely described.

   ➔ Broderick (2013,p.16) sees the necessity to better understand and describe these failure mechanisms. With reliable arguments investors are more likely to be convinced.

2. Colour Quality:

   Bad experiences with first generations of LED is hindering further application (In history, LED had colour deficits, which is now no longer true.) A better colour rendering description for LEDs is needed to better design lighting installations.

3. Lighting System Performance:

   Replacement bulbs are not standardized regarding control circuits, light distribution, light output etc. There can be significant colour mismatching between old and new replace bulbs.

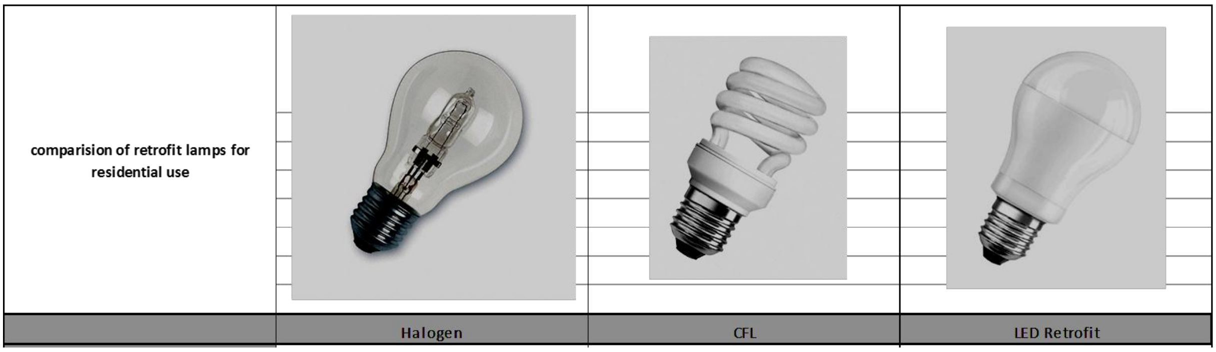
3 Lighting strategy: Retrofit vs. Replacement

The technical solutions in iNSPiRe are designed for LED for reasons described in the following chapters:

1. Investment – Payback Retrofit Bulbs
2. Investment – Payback Luminaire
3. Spectral Quality
4. Visual Quality

3.1 Investment - Payback: Retrofit Bulbs

The comparison below (Figure 22) shows three standard light sources for residential use with standard E27 sockets.



Type	Halogen Eco Pro	Duluxstar Twist	LED Star Classic
Watt [W]	46	11	10
Lumen [lm]	700	660	810
energy efficacy [lm/W]	15	60	81
price 2013 [€]	1.90	5.60	12.80

Figure 22 – Three considered lamps for comparison of retrofit intervention; Bartenbach market check, 2013

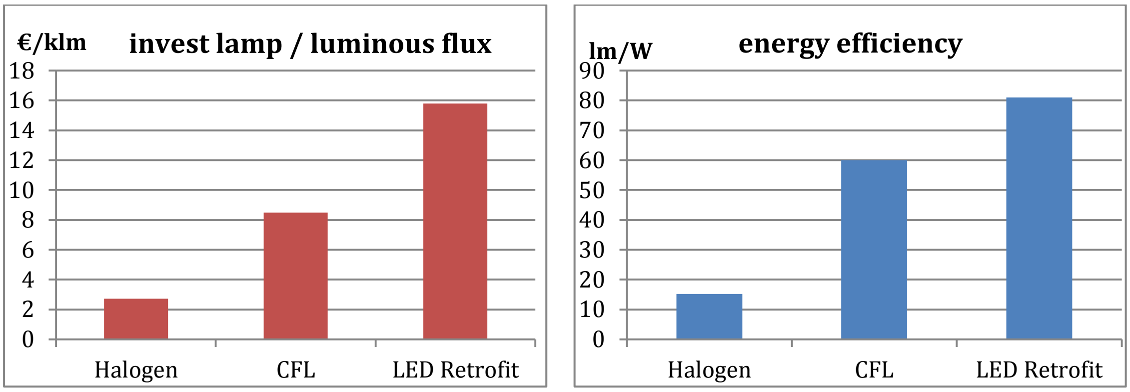


Figure 23 – Data of three samples for comparison

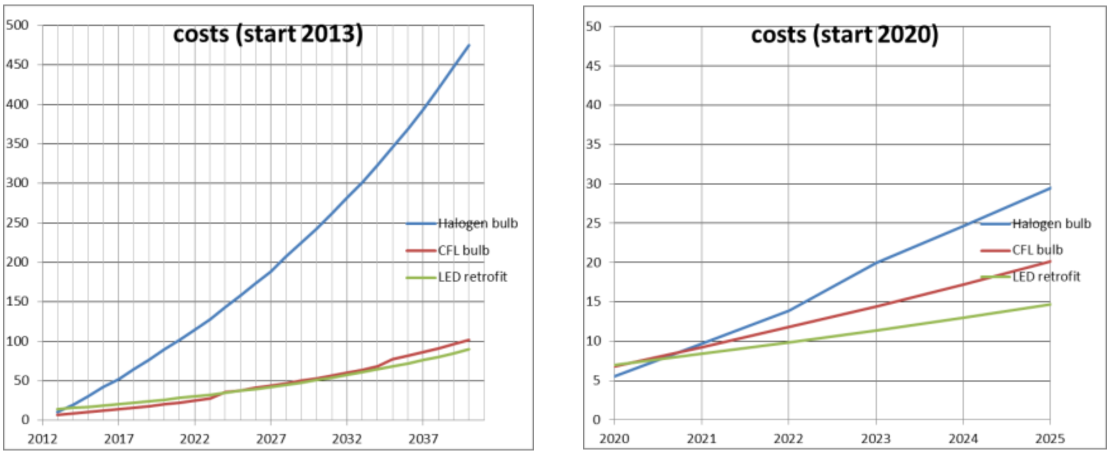


Figure 24 – Costs starting today; three bulbs assuming that all produce 660-810lm (left). Costs starting in 2020, with guessed efficiency and reduced prices (right)

Table 2 - - Lifetime costs inclusive of investment, electricity and lamp change intervals for Figure 23

price for bulb [€]	LED 12.8 (5.6 in 2020, today's EURO) CFL 5.6 (4.5 in 2020) Halogen 1.9 (1.9 in 2020)
Electricity household price in 2013 [€/kWh]	0.20
electricity price evolution [%/yr]	4.5
operating hours per day	2hrs/day
lifetime of light source (according to product datasheet) [h]	LED 25.000 (~34yr @ 2h/day) CFL 8000 (~11yr @ 2h/day) Halogen 2000 (~3yr@2h/day)
light source efficacy [lm/W];	LED 81 (estimated 120 in 2020) CFL 60 (estimated 70 in 2020) halogen 15 (estimated 35 in 2020)

In 2013 the halogen light bulb has the lowest investment costs compared to CFL and LED retrofits of same luminous flux. Nevertheless, its energy consumption and lifetime costs are much higher compared to the alternative light sources, because of the high relative energy costs. Starting the calculation of lifetime costs with products available in 2013 the payback time of a CFL compared to halogen is one year. The LEDs break even compared to Halogen is two years.

The investment costs of LED bulbs are about twice higher than a CFL. Considering the prices of 2013, the calculated breakeven point is located after approx. 11 years when the CFL reaches its defined lifetime of 8000 hours. At that point the investment costs for the additional lamp change give the LED the final benefit. After 20 Years the lifetime costs of the CFL are slightly higher than the LED retrofit.

Optimistic forecasting of this calculation for 2020 shows a different result: within one year, LED will payback higher investment cost (Figure 24). The uncertainty in this calculation is not defined but is based on assumptions mentioned in (Broderick 2012, 2013)

The high investment costs represent still a high barrier for investors. The payback time in comparison to CFL in residential and LFL in office application is today 12-14 years (see

Figure 24 for residential and Baumgartner et al. 2012, p.19 for office); it will decrease according to prognosis in (Baumgartner et al. 2012, p.19) to 0.5-3 years for investments done in 2020 (0.5 years for investments in residential application, 3 years in office application).

3.2 Investment – Payback: Luminaire

As described in chapter 2.1 the efficacy of the lighting system is integrally defined by the performances of all subsystems (lamp, controller and reflectors).

As seen in Figure 25 the large emitting surface of the CFL and its position relative to the reflector result in a bad luminaire efficacy. This relates to the fact that light is partly emitted outside of the reflector and/or emitted also upward (backward in orientation of reflector, in Figure 25). This backward light is partially reflected back to the light source. This luminous flux is partially lost for illumination. LED reflector design allows limiting the number of interactions of rays with reflector and LED, in fact they are restricted to one single bounce at reflector surface. The key feature is the small emitting surface. LEDs emit light in one single hemisphere. Due to this the distribution of the luminous 95% of the light emitted by the LED is available for the user (e.g. Light Output Ratio LOR = 95%).

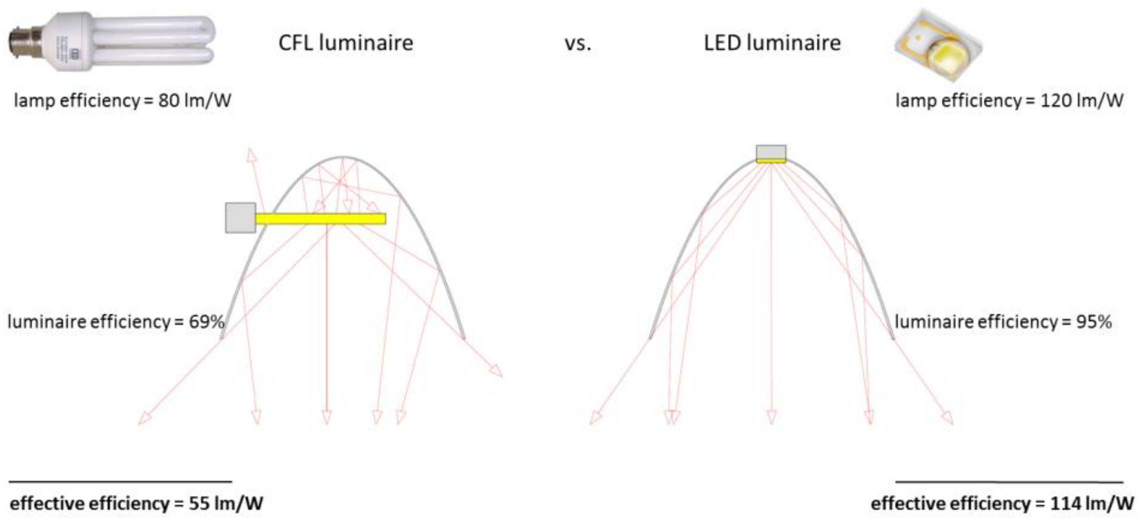
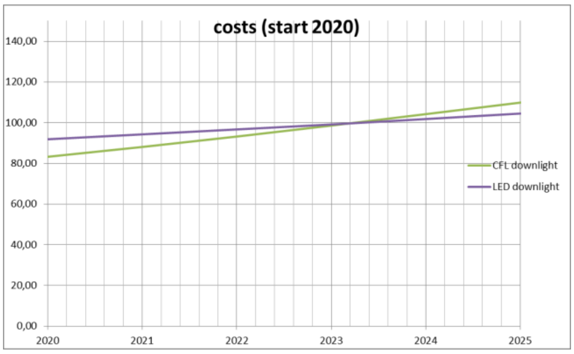


Figure 25 - efficiency scheme of CFL Downlights vs. LED Downlights

This LED downlights (Figure 25) is approx. twice more efficient than a CFL downlights. This is a significant input for payback times in Figure 26, where an office application was assumed with 3h/d operating time (for 250working days a year), a very well day lit office. Payback time is reduced from 10years down to two-three year for investments in done in 2020. In reality, due to double operating hours for standard buildings, the payback intervals are much smaller (4-5 year today, one year for investments in 2020) in Figure 60.



price for luminaire [€]	LED luminaire 120 (90 in 2020, today's EURO) CFL Luminaire 70 (80 in 2020)
electricity price in 2013 [€/kWh]	0.20
electricity price evolution [%/yr]	4.5
*op*erating hours per day	3hrs/day; 250d/yr
lifetime of light source (according to product datasheet) [h]	LED 25.000 (~33yr @ 3h/day) CFL 8000 (~11yr @ 3h/day) Halogen 2000 (~3yr@3h/day)
light source efficacy [lm/W];	LED 114 (estimated 140 in 2020) CFL 55 (estimated 80 in 2020)

Figure 26 - Luminaire lifetime costs

3.3 Spectral Quality

Spectral quality is also an important criterion for the comparison of CFL/LFL and LED for retrofit interventions. In this field, LEDs are able to outperform fluorescent light sources as further explained in this chapter.

The LED light source allows adjusting colour temperatures to different requirements of circadian (i.e. biological) demands for specific times of the day.

The colour characteristics of a light source is defined by its spectral power distribution (Pohl et al. 2013). There are numerous assessment criteria available, but none is standardized according to new visual models. Within the former standard DIN 5035-1, a definition of a classification of colour rendering levels was defined. This definition is in practical use up to now (Table 3).

To understand this Table 3: the higher R_a (or Color Rendering Index, CRI), the more natural do colours appear. DIN 5035-1 was replaced by DIN EN 12665 (Light and lighting - Basic terms and criteria for specifying lighting requirements) which does not contain any more a definition of "colour rendering levels".

But according to experience in lighting design, colour rendering is one of the most important characteristics of a lighting system. Colour rendering is assessed by using 14 test colours (Munsell colours in Figure 28). A test spectrum is compared with its closest reference spectrum at same Correlated Colour Temperature, Figure 29. For warm-white lamps a black-body spectrum, for cold-white lamps a daylight spectrum is referenced. The reference spectrum is projected onto the test colours, the re-emitted spectrum is measured and classified according to photometrical rules, i.e. coordinates in colour space $(x_{ref},y_{ref})_{testcolour,i}$ are calculated.

Table 3 - Colour rendering in categories

R_a	Category
90 - 100	1A
80 - 89	1B
70 - 79	2A
60 - 69	2B
40 - 59	3
20 - 39	4

The re-emitted spectrum of the test spectrum is also classified with colour coordinates $(x_{test},y_{test})_{testcolour,i}$. The distance between (x_{ref},y_{ref}) and (x_{test},y_{test}) for each testcolour defines the specific R_i value, which are shown exemplary in following figures. High R_i means that (x_{ref},y_{ref}) and (x_{test},y_{test}) are close in colour space. The closer they are the more likely are colours perceived as 'natural'. (R_i are sometimes negative, a result of metric in use) R_a (also called CRI) is the average of the first 8 R_i.

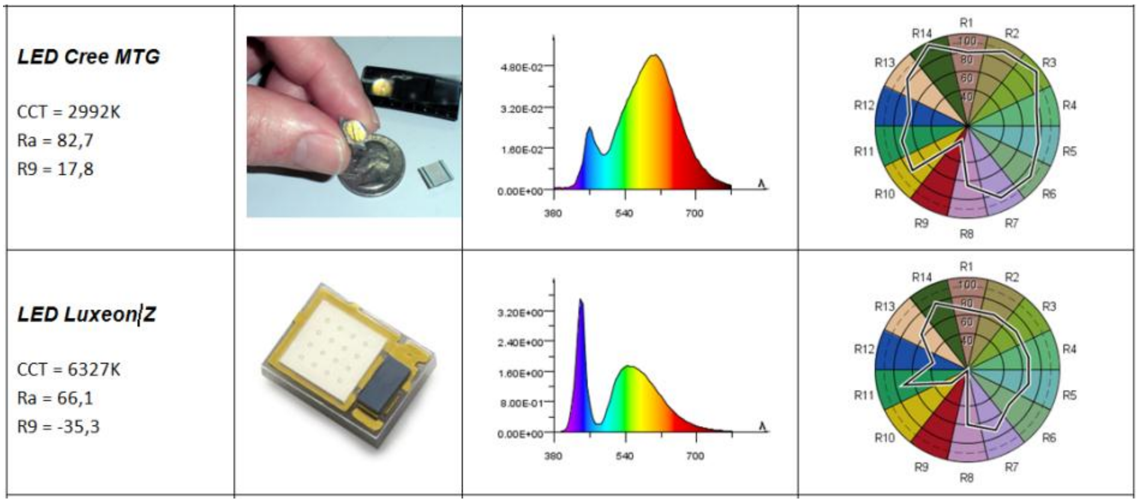


Figure 27 – LED are rated bad in R_9, which is according to visual studies not perceived as though.

The current colour rendering situation is complex, because LED are generally numerically assessed weak in R_9 (see Figure 27), whereas in visual perception tests, this was not found (Figure 27). Defining new colour rendering metrics is today topic of basic lighting research (Pohl et al. 2013).

Some examples of R_i and R_a are given in Figure 30 and Figure 31. The incandescent bulb is rated with R_a = 100, which is obvious since the glowing wire is a black body. High efficient fluorescent tubes are generally weak in R_a. Again, the price to pay for a higher Ra is generally a lower efficacy.

Figure 28 – Munsell test colours (14)

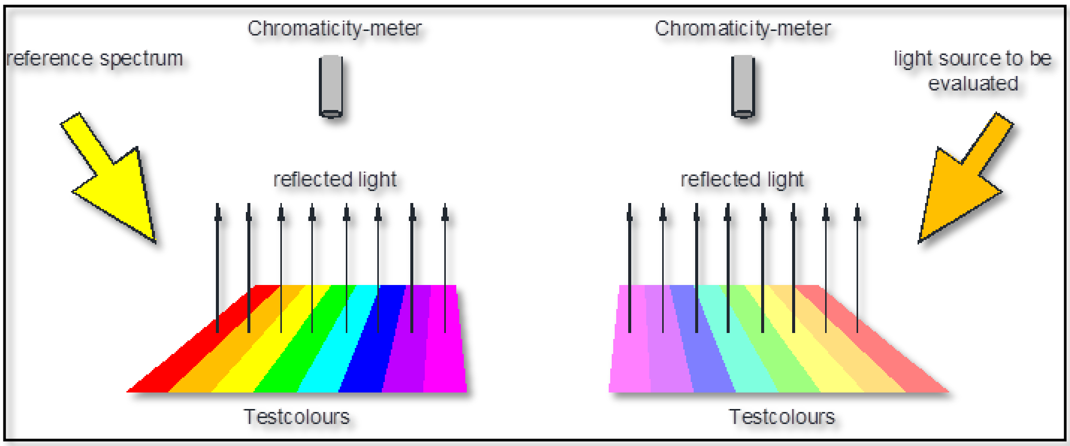


Figure 29 – Definition of CRI (or R_a) calculation. The light-source to be tested is compared with a reference spectrum that has the same correlated colour temperature.

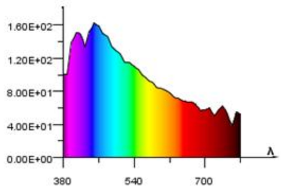
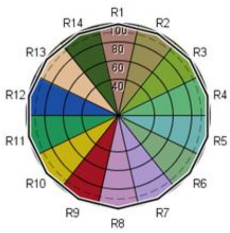
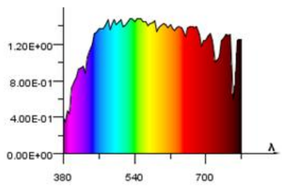
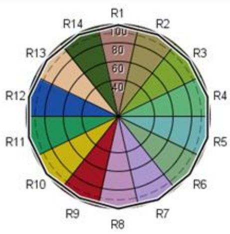
Blue Sky (example, real measurement by Bartenbach) CCT = 10009K Ra = 100,0			
Direct sunlight (example, real measurement by Bartenbach) CCT = 5186K Ra = 99,4	 2		

Figure 30 – R_i and R_a for Blue sky and direct solar beam

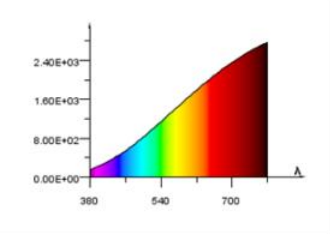
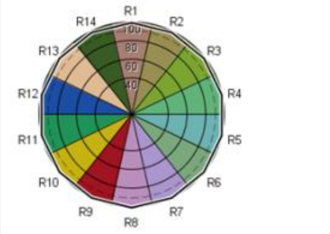
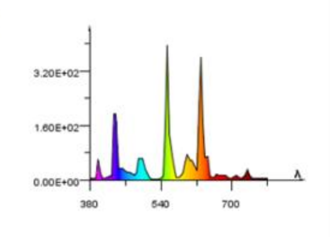
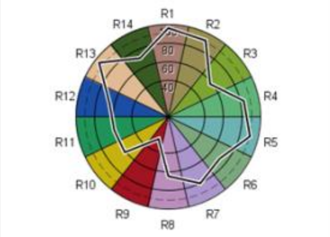
Incandescent CCT = 3000K Ra = 100,0 R9 = 100,0			
Fluorescent tube 840 (this is standard) CCT = 3547K Ra = 79,8 R9 = 26,2			

Figure 31 - R_i and R_a for incandescent and fluorescent tube.

3.4 Visual Quality

Due to above mentioned small geometry of LED, optical design is more precise. Precision is needed for light intensity distribution defined by specific needs (e.g. working area, walking area, etc.). Erroneous light intensity distributions are likely to cause glare (high luminances) or waste light, because it is distributed to areas where it is useless for specific tasks. LED luminaires allow very brilliant sceneries (including shadows) whereas CFL/LFLs generate soft and dull sceneries, i.e. things appear soft (Figure 32). Shadows are supporting the environment modelling (environment is 3dimensional). A well rendered environment enhances visual comfort and productiveness.

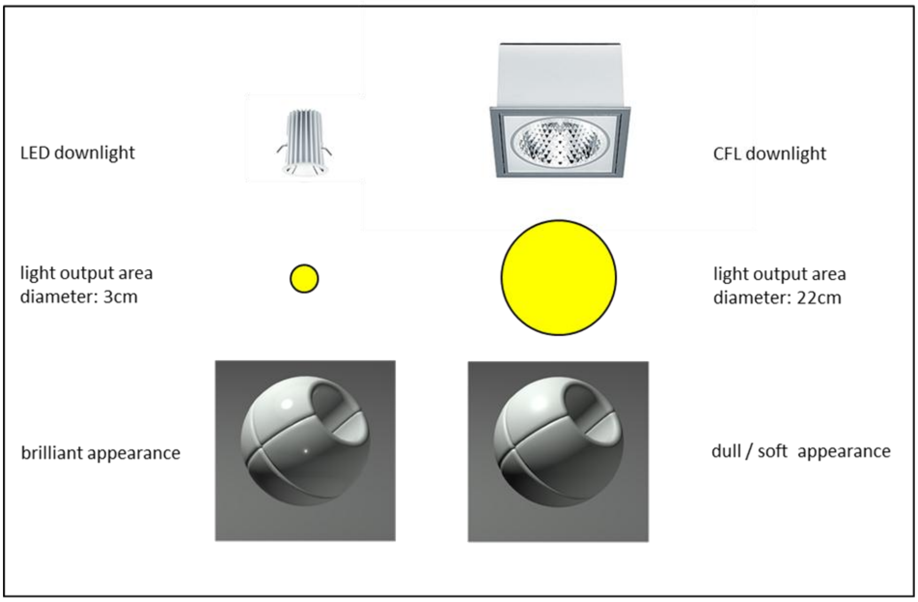


Figure 32 - different appearance of varying light output areas. LED light sources appear much more brilliant.

4 Market Analysis and Visual&Spectral Quality Conclusion

Retrofitting residential lighting installations may happen by replacing old bulbs by CFL or LED (in existing sockets) or replacing the whole luminaire. Both approaches will yield today to a very significant efficiency rise if incandescent or halogen systems are replaced.

European regulations will cease the sale of any inefficient light sources or integrated luminaire. Already in a near future, any residential applier will have to choose between “efficient CFL” and LED solutions. In both cases LED’s spectral qualities bring this solid state lighting in front. In very near future, LED will outclass CFLs in efficacy, accordingly undershoot costs for purchase and usage, and payback time will come down to one to three years. As shown above, life cycle analysis point out that LEDs will be far less harmful to our environment than any other light source latest in 2016.

LED light source allows adjusting spectral power distribution to different requirements of colour rendering and circadian (i.e. biological) demands for specific applications at certain times of the day.

Summing up, existing possibilities in optical/visual design and all future prognosis demonstrate clearly that LEDs are already today the proper solution to invest in research, development and installation (in retrofit or in luminaire replacement).

Consequently, within iNSPiRe focus is laid on LED luminaire design.

5 Solutions for integration into the distribution kit

Based on the conclusions in chapter 4 the development in iNSPiRe are focusing on solid state lighting (LED).

5.1 Residential solution

The general idea is to integrate luminaires into ceiling panels in order to provide apartments and their users with a solution that is cheap and easy to assemble yet fulfilling visual and efficiency requirements. In the following subchapters, the process of defining the solutions for residential applications is shown. It will result in demonstrators of a pendant luminaire for living/dining rooms and a LED spot solution for general illumination. These both solutions will be accompanied by a more simple but diffuse luminaire.

In order to guarantee a flexible position of the luminaires, the panel will be prepared with a grid (or delivered with a specific ruler) of possible positions for an excavation (i.e. additional holes). The user or craftsmen will then put the iNSPiRe luminaire into one or more of these holes. If known, the manufacturer will deliver panels with holes already drilled or luminaires already integrated into the panel. In this case, the prefabrication provides maximum performance of both systems. If the user desires rearranging his home, he/she is able to move the luminaire to freshly drilled holes and cover the old ones with an already delivered cover, so that the hole is not visible any more.

As experience tells, residential users are used to live in poorly illuminated environments (average ~ 50lx). It appears not reasonable to go for much higher illuminance levels (300-500lx as required in office applications). Alternatively, the project iNSPiRe tries to convince that, at least, zoning (i.e. increasing illuminances according to specific tasks) is absolutely necessary for an improved comfort (visual), while not increasing the average illuminance significantly, which would be contradicting to the idea of reducing energy.

Table 4 - Typical average illumination levels for dimensioning of lighting energy demands in residential sector; additional specific task related zoning is obligatory.

Area	average illuminance levels [lx]
living room	50
dining room	50
Kitchen	100
kids 1	50
kids 2	50
Bedroom	50
bathroom	100
Hallway	50

To size the required luminous fluxes, the illuminance levels are multiplied by some representative room dimensions in apartments and condominiums:

Table 5 - Typical living areas for rooms

standard room sizes	
space [m²]	Room
2	WC
5	bath, kitchen
10	Kitchen, kids, hallway, dining room.
15	Bedroom
20	Living room
25	combined living- dining room

iNSPiRe focuses on two approaches for maximizing flexibility:

- a ceiling panel with integrated radiant heating/cooling and integrated iNSPiRe luminaires; fully integrated at manufacturer's site.
- a ceiling panel with integrated radiant heating/cooling and the possibility to include any arbitrary luminaire at construction site (installation on-site by owner or craftsmen). So the user has full flexibility to fulfil his lighting design preferences (arbitrary luminaire means, iNSPiRe luminaires or any other product).

The foreseen impact of combined lighting systems is depending on how it

- covers the general visual requirement,
- covers financial, (investment and lifecycle) concern,
- covers economic concerns and
- covers design and flexibility wishes.

5.1.1 Pendant luminaire

The main design driver for this solution is the idea of illuminating one room out of one single position, which reduces the actions on the ceiling panel. Lighting the whole room out of one single point within the ceiling is not possible without glare problems. The lighting installation must provide a general illumination and specific task and space related zone illumination. Therefore a secondary structure is needed for distributing the light within the room – using the ceiling as distributor. The pendant luminaire consists of a light source (3x3 grid) embedded into the panel and a suspended reflector /prism device that provides a direct and indirect light distribution (Figure 33).

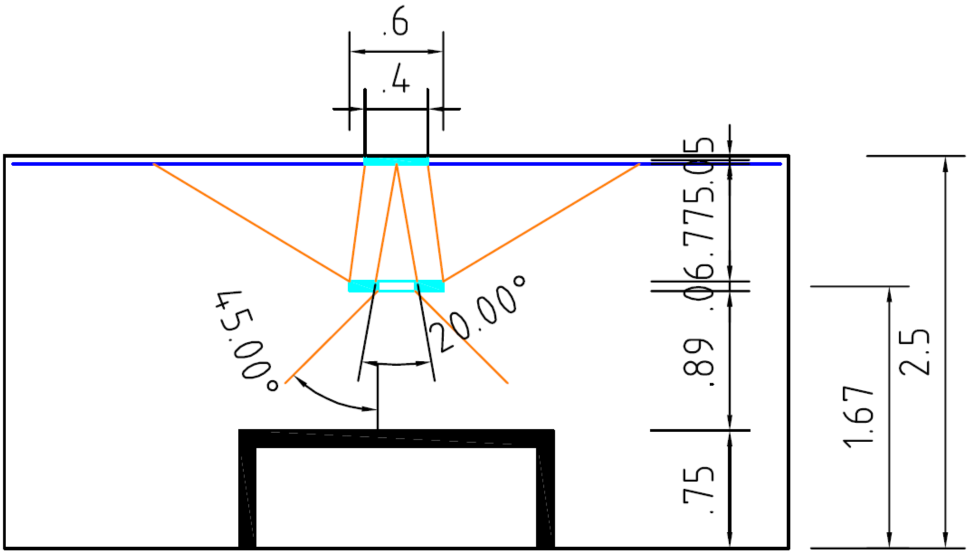


Figure 33 – a living room of 20m² in vertical section; the suspended reflector is hung 60-80cm from the ceiling.

The luminaire produces a structured luminance distribution at the ceiling as well as a perfectly non-glaring zoning on the table or working plane (Figure 34). The distribution on the ceiling will be available also in ‘smooth option’, without patterns. The patterns on the ceiling will be adjustable to the position of the luminaire within the room, by tilting the little mirrors on top of the secondary structure (Figure 36, right). The direct illumination for tables is realized by 3D - printed lenses, which reduces the costs significantly.

The luminous output is appropriate for rooms up to 20 m², which are considered to be standard rooms in target buildings of iNSPiRe.

The LED light source allows adjusting colour temperatures to different requirements of circadian (i.e. biological) demands for specific times of the day (Melatonin-adapted in night times and daytimes).

The target price for this luminaire is 600-800€, which is - as punctual contacts to target group is showing - bearable.

Figure 34 - rendered visualization of the pendant luminaire with direct & indirect lighting distribution (two patterns)

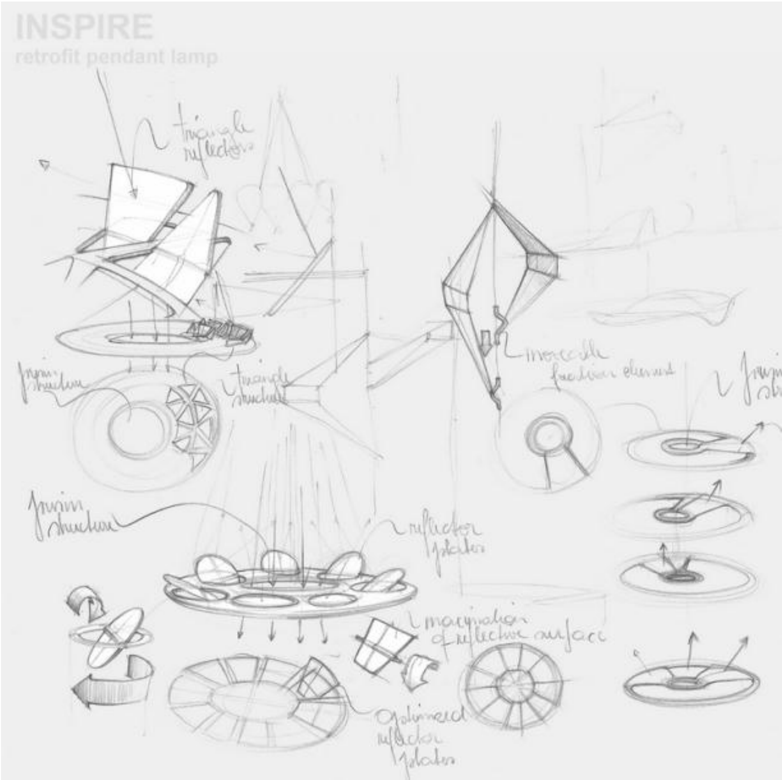


Figure 35 - design ideation

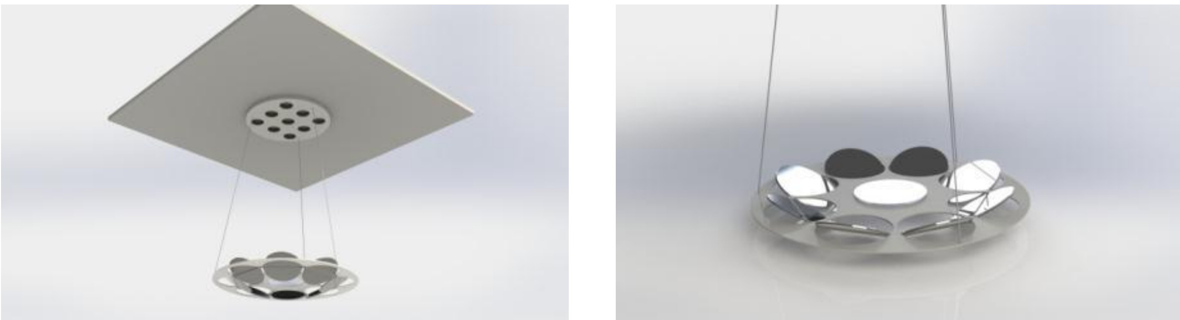


Figure 36 – Mechanical and optical concept of pendant luminaire. The light engine (LED + controller) is integrated into the multifunctional panel.

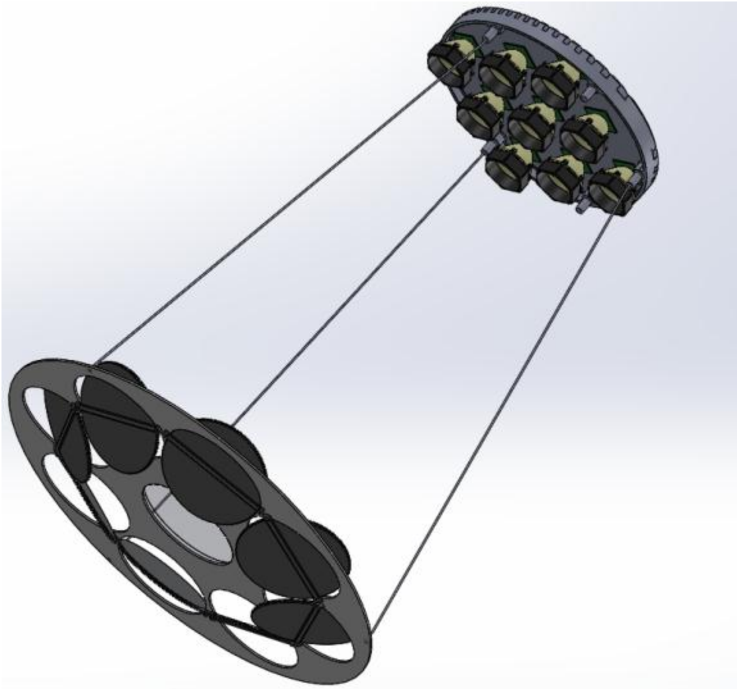


Figure 37 – Pendant luminaire, technical drawing; Pendant consisting of a 3x3 array of optics with a suspended reflector and lens system.

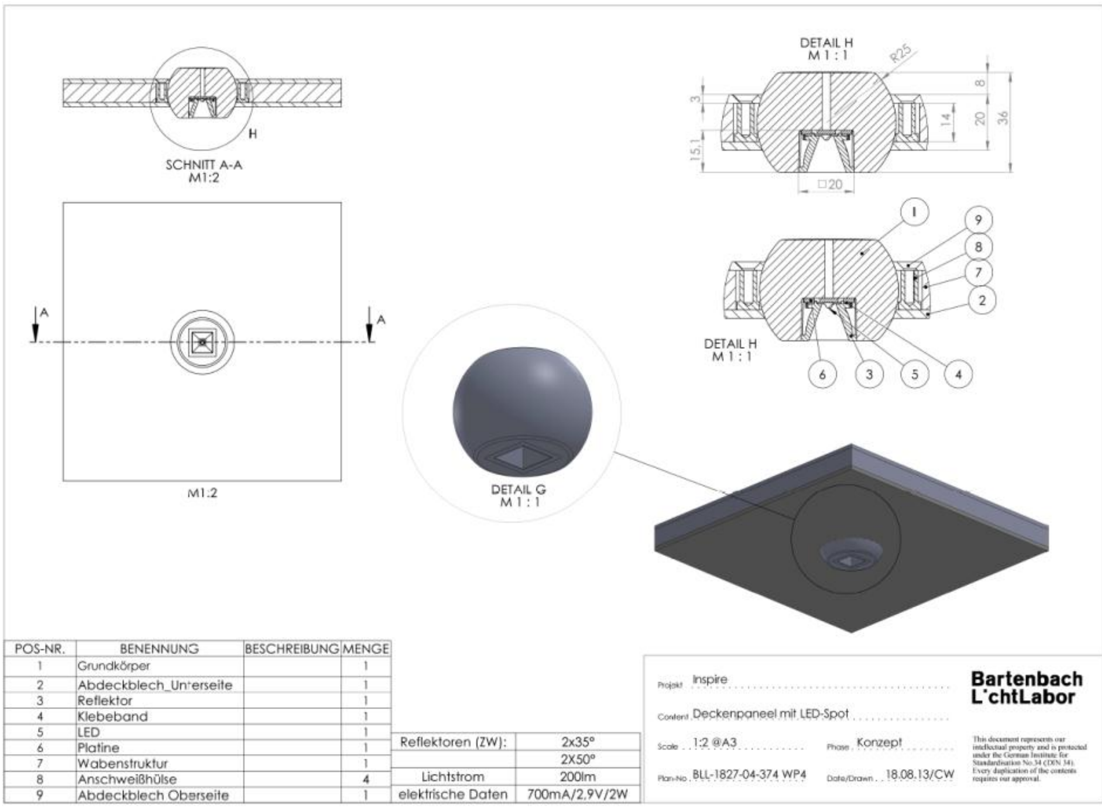


Figure 38 –recessed LED spot

5.1.2 Recessed Luminaire

General illumination and zoning is also possible with many separated light points. This approach is followed by this solution (see Figure 38). A defined set of point-like source is used for general illumination (wide ~ 80° and very wide beams ~ 100°) with additional spots (narrow beams ~40°) for zoning above tables or reading zones. The Recessed Luminaire can be smoothly integrated into the panel and 3D rotated to give the user full flexibility to position the light source according to his/her needs. He/She or the ceiling manufacturer will do the integration.

Some synergies exist between the lighting and radiant thermal functions of heating/cooling ceiling panels: indeed the sphere will use the heating panel as heat sink, which is already today only slightly beneficial as Hot2Cold[1] factors are now at 10% and will further decrease as LED manufacturers are delivering new generations of LED packages in quarter-years periods., (e.g. Philips will start to sell a specific heat insensitive package beginning of 2014). The design of these spheres (spots) will be still optimized regarding LCA. A Variation between bodies made of aluminium or PMMA and reflectors made of PVD or aluminium is investigated.

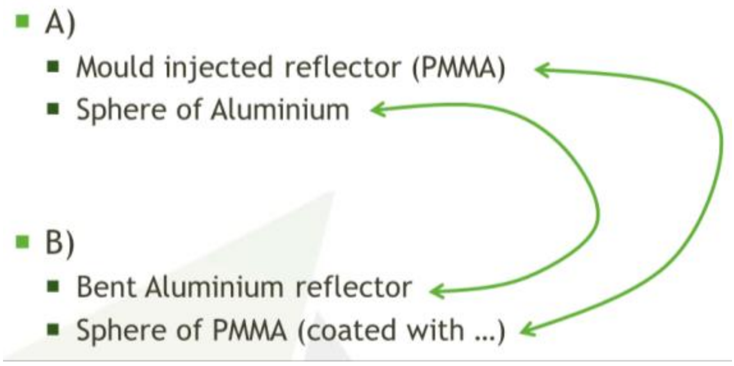


Figure 39 – Variation of LED Spot design. Aluminium or PMMA

5.1.3 Diffuse flat

Alternatively for traffic zones or zones with minor visual requirements diffuse panels are proposed. The solution is ready as all single components are off-the-shelf available. An LED stripe is emitting light into one e.g. Plexiglas / or real glass panel, which is punctually printed on top surface. Thanks to total reflection light cannot leave the panel unless it is transformed by the diffuse printed areas on top side. By adjusting the printing structure the appearance of the glass panel is homogeneous diffuse.

[1] Hot2Cold … luminous output decrease between 25°C and 100°C

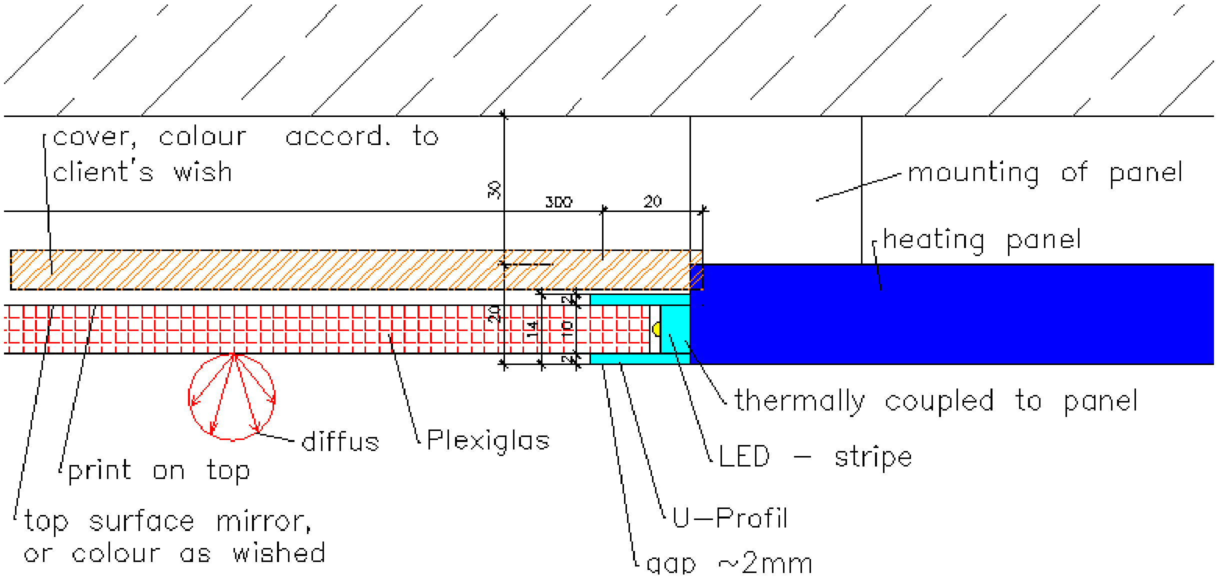


Figure 40 – draft of 'Diffuse flat' solution, using off-the-shelf components.

Figure 41 – 'Diffuse flat' as perimeter to the island installation of the heating panel. For illustration used in living and bedroom, where it won't be used, instead hallways, bathroom, etc.

5.1.4 A case study

Applied on a generic case study (Figure 45), we can estimate investment costs and energy consumption of each lighting solution, replacement by

1. Halogen based Luminaire
2. Fluorescent based Luminaire
3. LED based luminaire
4. Retrofit by CFL bulb
5. Retrofit by LED bulb

A qualitative description of these five solutions is given below (Figure 42):

Luminaire replacement						Lamp replacement			
Halogen luminaire 18lm/W		Flourescent luminaire 80lm/W		LED luminaire 140lm/W		Duluxstar twist (70lm/W) eta_luminaire~70%		LED retrofit E27 (120lm/W) eta_luminaire~70%	
power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]
_low invest / high operating costs		_medium invest /low operating costs		_high invest /low operating costs		_low invest /low operating costs		_high invest /low operating costs	
_no mercury		_mercury		_no mercury		_ mercury		_no mercury	
_excelent spectral distribution		_bad spectral distribution		_excelent spectral distribution		_bad spectral distribution		_excelent spectral distribution	
_brilliant appearance		_dull appearance		_brilliant appearance		_dull appearance		_brilliant appearance	

Figure 42 – Five considered solutions

Operational and investment costs are calculated using the required luminous flux. The power consumption is calculated taking the individual lm/W ratio into account. The investment costs relate to lm/€ ratio and a factor for building a luminaire for the lamp. Operating costs are the accumulation of yearly energy costs over the considered timeframe, taking the usual inflation rate of 4.5% into account.

Two scenarios are compared for a timeframe of 20 years:

a) Investment today, in 2013 (Figure 45)

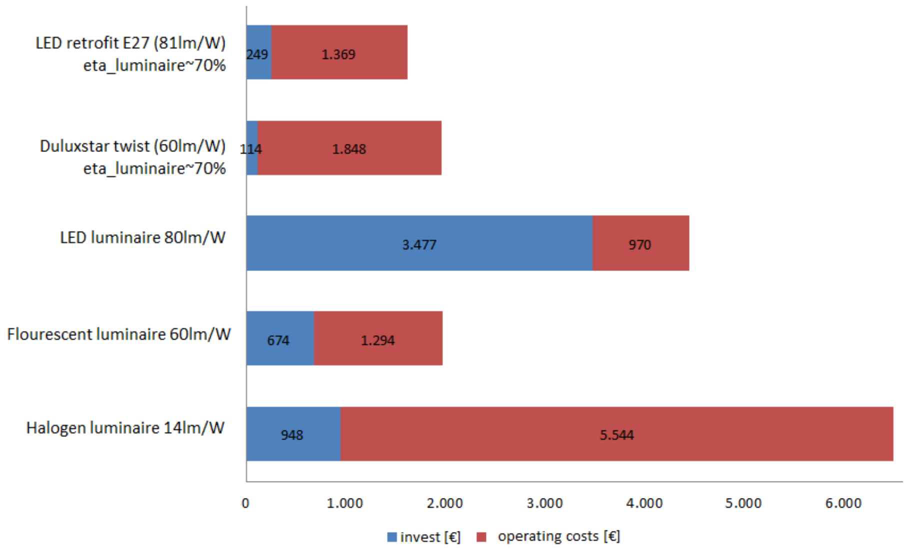


Figure 43 – Costs for investment today

As presented in Figure 43, investment for LED is 4 times the investment for Halogen. Fluorescent is not really an option for full installation in residential application due to its poor colour rendering qualities. The cheapest intervention is definitely the replacement by LED retrofit bulbs, but regarding also energy consumption (end energy) it is the LED luminaire that has smallest end-energy demand (Figure 45). This luminaire will also provide best spectral distribution (again, colour rendering and biological impacts), brilliance, longer lifetime and mercury free construction.

b) Investment in 2020 (today's EUROs) (Figure 46)

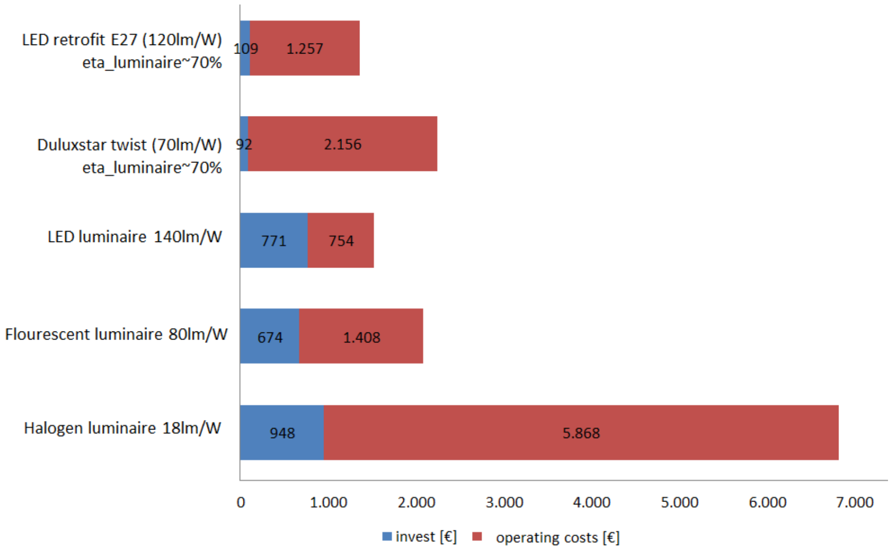


Figure 44 – cost for installation in 2020 (with today's EURO)

An Installation in 2020 will probably balance the numbers shown in Figure 44. While Halogen Luminaires won't be available any more (the reason of poor efficacy is obvious) LED luminaires will optimistically be the cheapest solution; regarding finances and end-energy.

Applied on case study					Luminaire replacement						Lamp replacement			
room type	area [sqm]	illuminace [lx]	luminaire	luminous flux	Halogen luminaire 14lm/W		Flourescent luminaire 60lm/W		LED luminaire 80lm/W		Duluxstar twist (60lm/W) eta_luminaire~70%		LED retrofit E27 (81lm/W) eta_luminaire~70%	
					power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]
living room	23,22	50	pendant	4146	296	250	69	178	52	916	99	30	73	66
dining room	9,04	50	pendant	1928	138	116	32	83	24	426	46	14	34	30
kitchen	6,61	100	recessed	1879	134	113	31	81	23	415	45	14	33	30
kids 1	10,12	50	recessed	1439	103	87	24	62	18	318	34	10	25	23
kids 2	10,24	50	recessed	1456	104	88	24	62	18	322	35	11	26	23
bedroom	14,61	50	recessed	2077	148	125	35	89	26	459	49	15	37	33
bathroom	5,27	100	recessed	1498	107	90	25	64	19	331	36	11	26	24
hallway	9,24	50	recessed	1313	94	79	22	56	16	290	31	10	23	21
total					power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]
	area				**1.124**	**948**	**262**	**674**	**197**	**3.477**	**375**	**114**	**278**	**249**
	88,35	**compared with halogen solution**			**100%**	**100%**	**23%**	**71%**	**18%**	**367%**	**33%**	**12%**	**25%**	**26%**

estimation of power consumption and operating costs

			Halogen		flourescent		LED		CFL E27		LED retro	
in use /day in [h]	**2**		end energy [kWH]	cost [€]	end energy [kWH]	cost [€]	end energy [kWH]	cost [€]	end energy [kWH]	cost [€]	end energy [kWH]	cost [€]
n use days/year in [d	365											
years	20		32.011	**5.544**	7.469	**1.294**	5.602	**970**	10.670	**1.848**	7.904	**1.369**
€/kw	4,5%/yr	starting 0.2€/kWh										

Figure 45 - cost estimation for case study, investment in 2013

Applied on case study					Luminaire replacement						Lamp replacement			
room type	area [sqm]	illuminace [lx]	luminaire	luminous flux	Halogen luminaire 18lm/W		Flourescent luminaire 80lm/W		LED luminaire 140lm/W		Duluxstar twist (70lm/W) eta_luminaire~70%		LED retrofit E27 (120lm/W) eta_luminaire~70%	
					power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]
living room	23,22	50	pendant	4146	230	250	55	178	30	203	85	30	49	66
dining room	9,04	50	pendant	1928	107	116	26	83	14	94	39	14	23	30
kitchen	6,61	100	recessed	1879	104	113	25	81	13	92	38	14	22	30
kids 1	10,12	50	recessed	1439	80	87	19	62	10	70	29	10	17	23
kids 2	10,24	50	recessed	1456	81	88	19	62	10	71	30	11	17	23
bedroom	14,61	50	recessed	2077	115	125	28	89	15	102	42	15	25	33
bathroom	5,27	100	recessed	1498	83	90	20	64	11	73	31	11	18	24
hallway	9,24	50	recessed	1313	73	79	18	56	9	64	27	10	16	21
total					power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]	power[W]	invest [€]
	area				**874**	**948**	**210**	**674**	**112**	**771**	**321**	**114**	**187**	**249**
	88,35	**compared with halogen solution**			**100%**	**100%**	**24%**	**71%**	**13%**	**81%**	**37%**	**12%**	**21%**	**26%**

estimation of power consumption and operating costs												
in use /day in [h]	**2**		Halogen		flourescent		LED		CFL E27		LED retro	
n use days/year in [d	365		end energy [kWH]	cost [€]	end energy [kWH]	cost [€]	end energy [kWH]	cost [€]	end energy [kWH]	cost [€]	end energy [kWH]	cost [€]
years	20		24.897	**5.868**	5.975	**1.408**	3.201	**754**	9.146	**2.156**	5.335	**1.257**
€/kw	4,5%/yr											
consumed lifetime in [%]			7,30		0,73		0,29		1,46		0,29	

Figure 46 - cost estimation for case study, investment in 2020

5.2 Office solution

5.2.1 Requirements

- 500 lux on working plane - relates to the requirements in EN 12464
- Spotlight up to 1000 lux on working plane - relates to improved task performance
- Dimmable, tunable (adaption to entering daylight, circadian adapted)
- Correlated colour temperature 4000k (adaption to entering daylight)
- Highly efficient lamps
- Lighting system embedded into ceiling panel, prefabrication
- Interaction with daylight (ceiling structure)

5.2.2 Solutions

Office lighting is today dominated by fluorescent luminaires. As discussed above, highest efficacy can't be achieved by replacing lamps. It is again the integral design of LED luminaires that achieves highest efficiency in near term future.

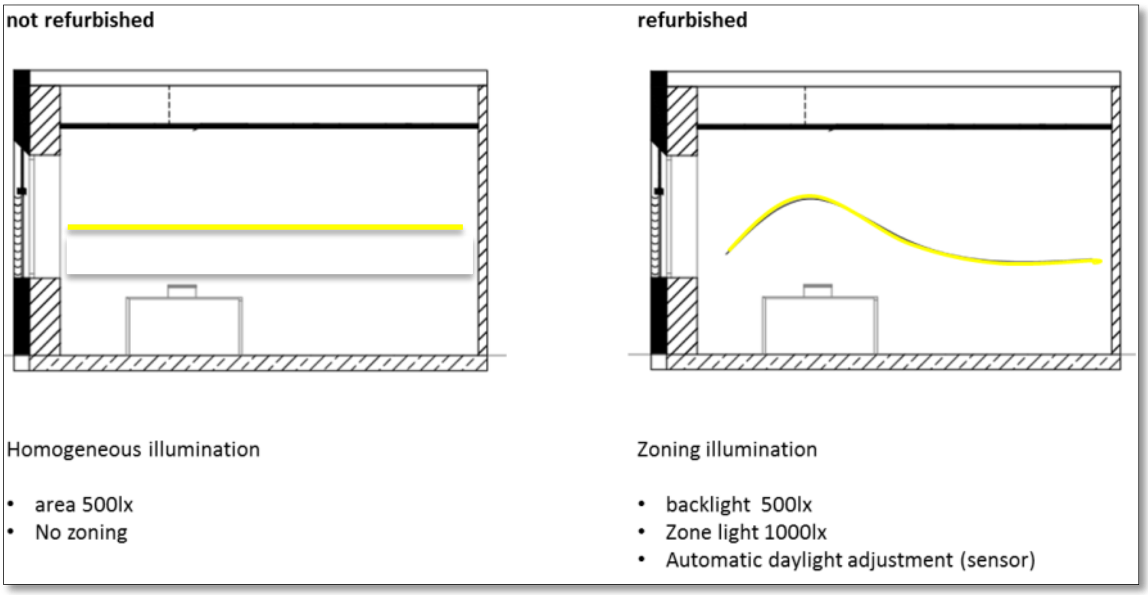
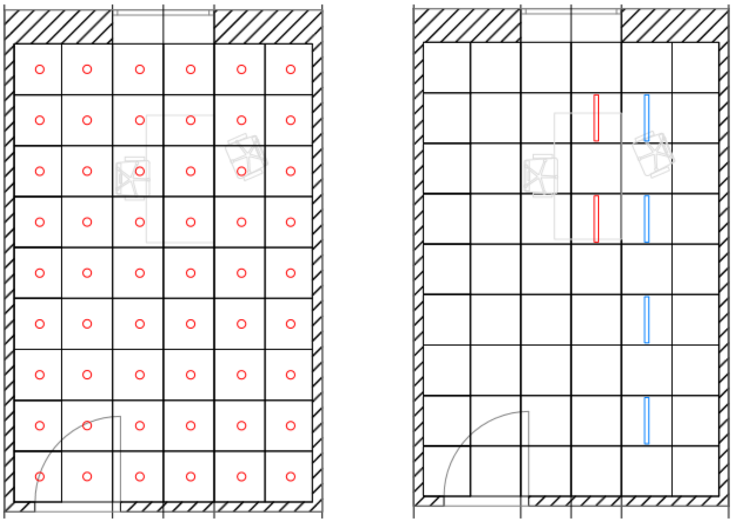


Figure 47 – paradigm of zoning

Starting point for all discussions in this task was a point-like illumination concept. The main goal of the intervention is to increase zoning illuminance for enhanced working performance (Figure 47).

A point-like installation provides highest flexibility for illumination. It is this installation that allows a possible full rearrangement of the office interior.

Based on standard ceiling structures of 60x60cm² plasterboard elements, the idea of installing LED points in each of these elements was born. For current maximum lumen packages per point, this would result in 54 installations for a 21m² room. In comparison, for linear elements, it's sufficient to install only 2 downlights and 4 wallwashers (Figure 48). This fact reasons the installation of linear elements instead of point like luminaires.



54 Downlights on 21m²

2 Downlights and 4 wallwasher on 21m²

Figure 48 – installation concepts for 21m² office room

Further reduction of panel integration and maintaining flexibility for user is proposed by including the main luminaire (called window luminaire in Figure 49) for office illumination in the façade and using the ceiling structure for both day- and artificial lighting. The transparent façade is going to integrate a daylight redirecting lamella, which is redirecting onto the ceiling. A standard white or diffuse surface does not allow specific daylight illumination levels on working plane. Therefore the surface on the ceiling, in this case, the surface of the heating or cooling panel is designed for working as day- and artificial light distributor. For daylight purpose this approach is financially inefficient, but a synergetic use with the artificial lighting system is beneficial.

In times of low daylight availability the main luminaire will feed the illuminance levels with adapted intensity and colour temperature (adapted to the exterior daylight scene (e.g. cold white or warm white at specific times of the day) or adapted to circadian demands (activating at specific times). The panel will be installed perpendicular to the façade, as island or full installation. The size of subdivision 1 in Figure 50 is optimized according to the layout of the building. Subdivision 2 will be illuminated by additional components (Figure 51 and Figure 52).

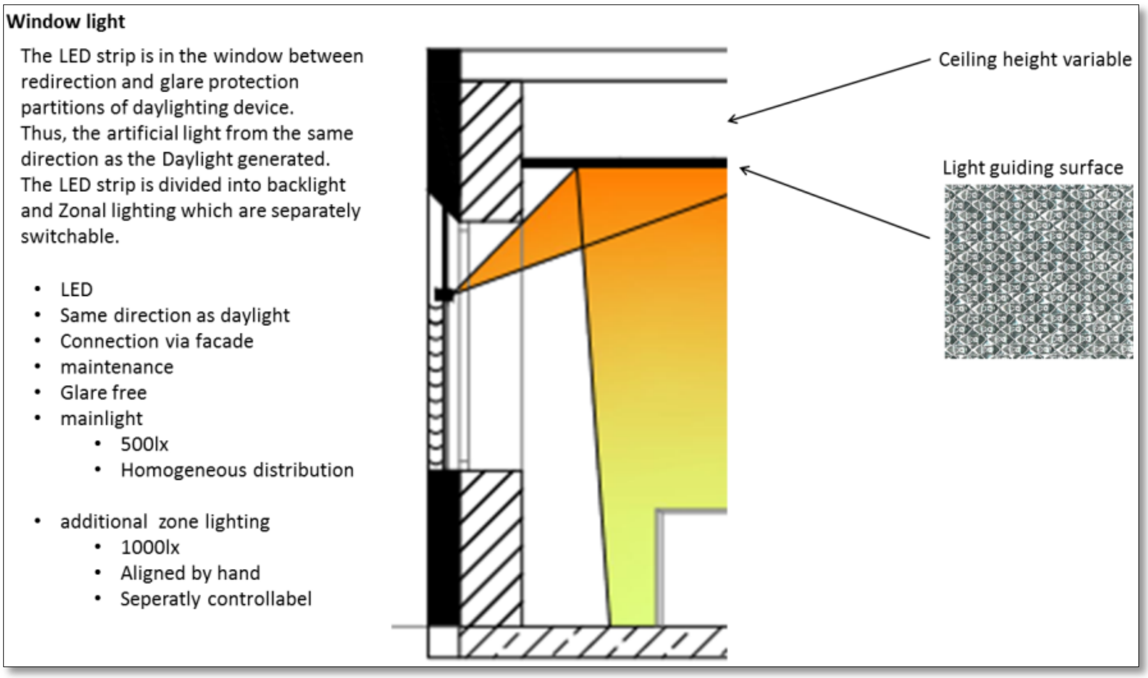


Figure 49– Ceiling washer integrated into façade and interacting with the same structure as daylight does.

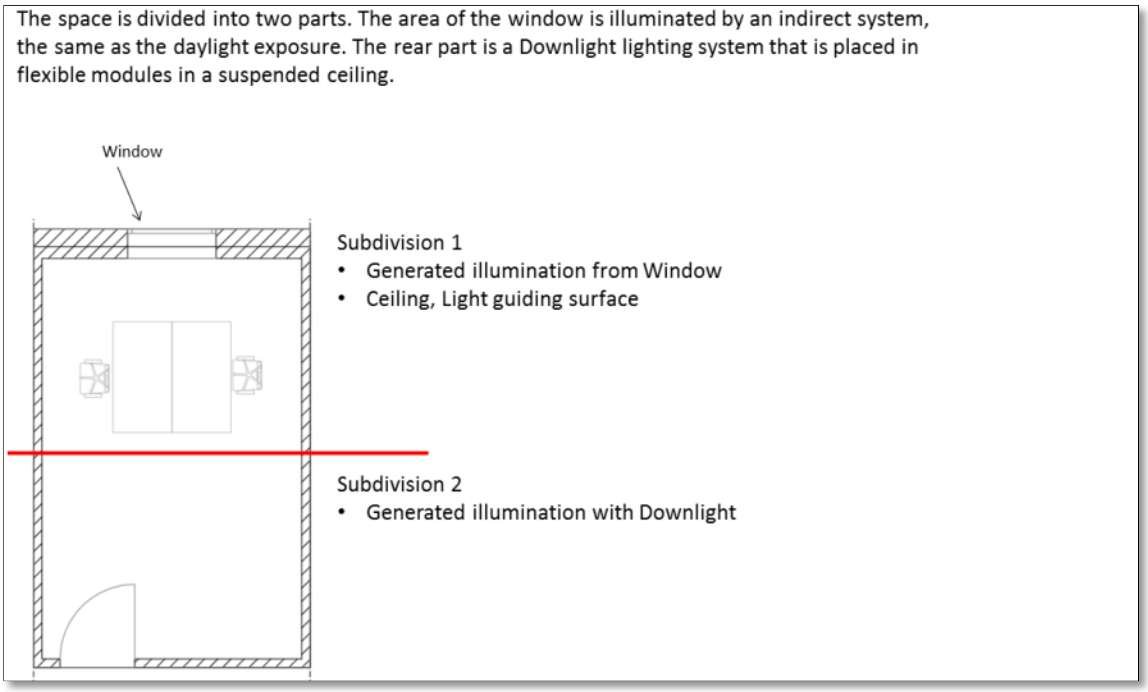


Figure 50 – Illustration and definition of wording: subdivision

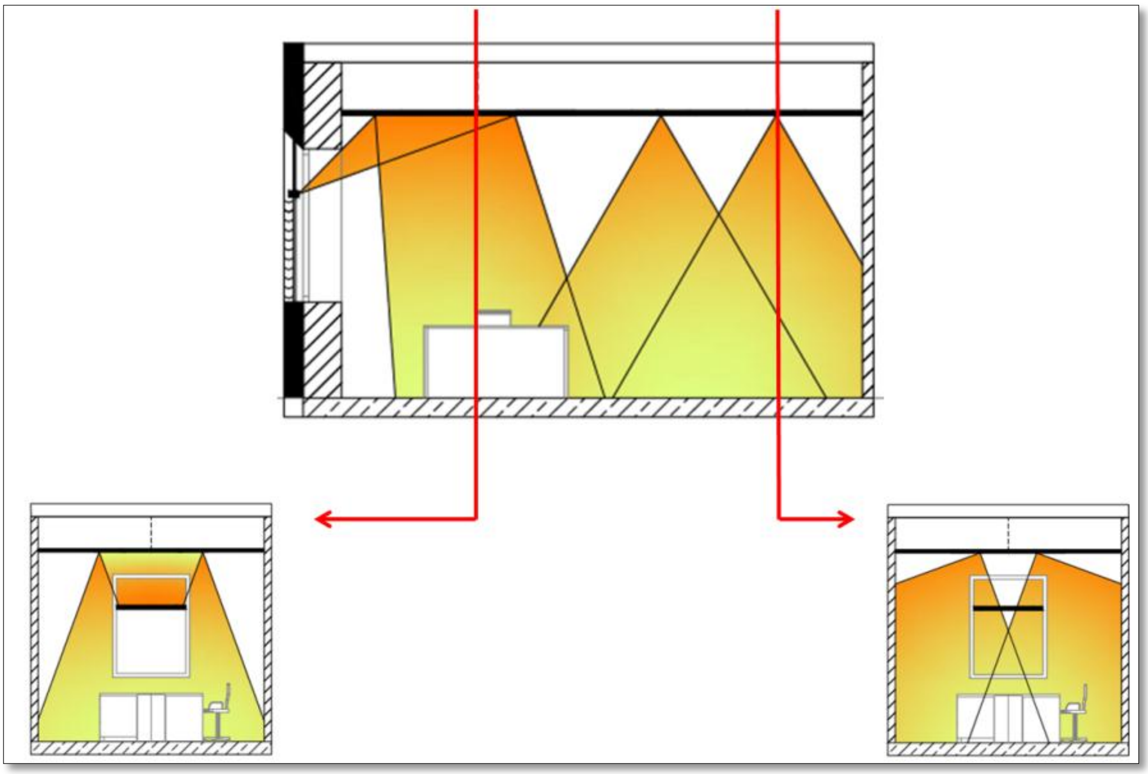


Figure 51 – Main illumination

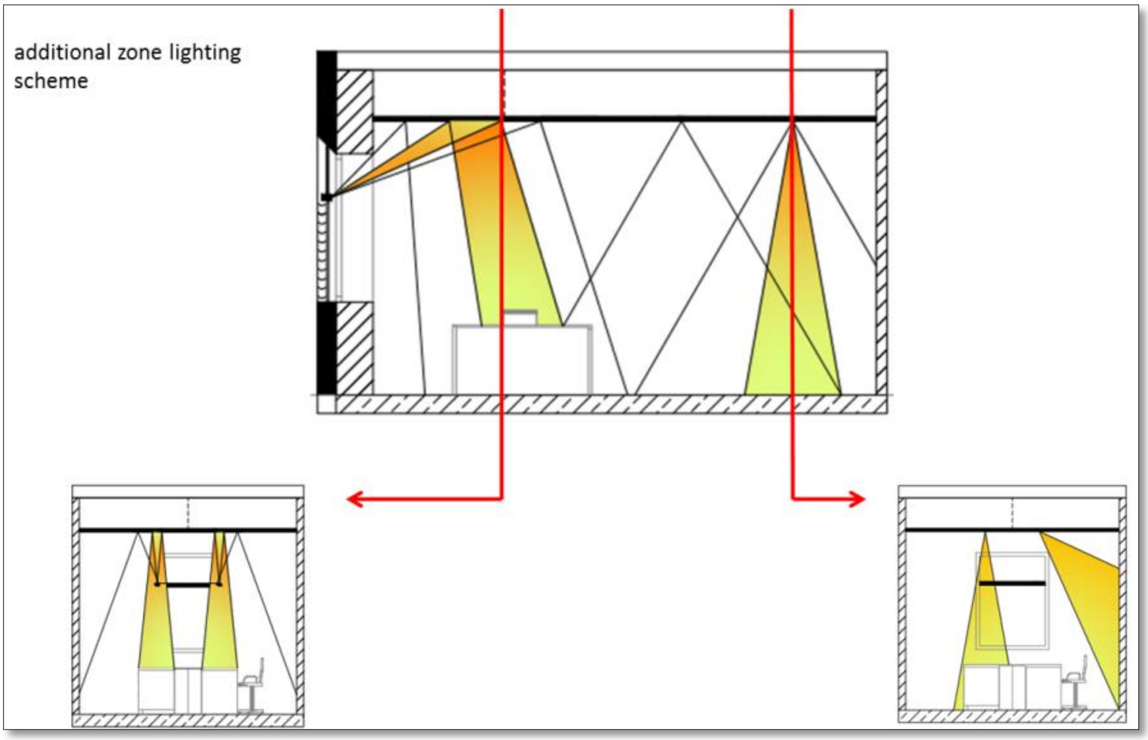


Figure 52 – Zoning, additional

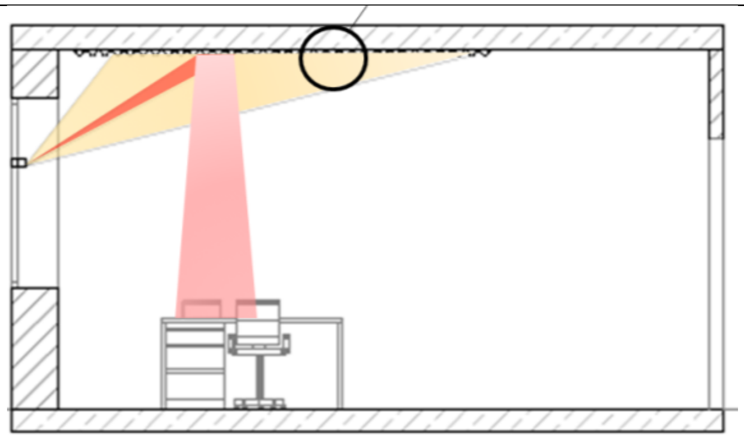
5.2.3 Components

The development is focussing on linear elements, which can be integrated into ceiling panels as well as onto the façade.

Following benefits are foreseen:

- One prepared opening in the panel fits all: downlights , wallwasher & ceiling washer
- The linear elements are ‘clickable’ (i.e. pluggable) into the panel, they are all the same size. Installation costs are minimized.
- The hole is prepared at manufacturer’s site. The covers of these holes can be replaced by the luminaires on construction site. The space between two adjacent panel is kept free for the luminaires (a cover will hide this gap, if no luminaire is installed).
- They are suitable for all office types due to alignment parallel or perpendicular to the façade.
- The set of luminaire fits all geometries (subdividing room geometries).

5.2.4 Ceiling Washer in interaction with panel surface

ceiling washer integrated into facade Main illumination at working plane ~ 500lx Surface of top structure is used for daylight as well as for artificial light	

The ceiling washer is connected to the façade element at its interior surface. By using a specific structured surface (e.g. Figure 53) of the heating panel, this solution offers highest flexibility. Single, double or open-plan offices can be illuminated from the façade.

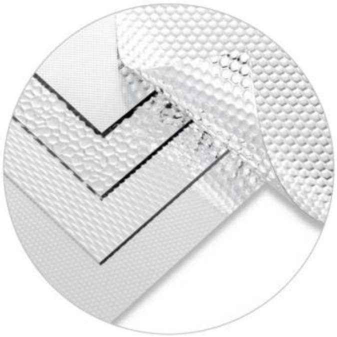


Figure 53 – different highly reflective structures (www.alanod.com)

Figure 54 - Light engine for installation at façade (www.projektleuchten.de)

Each reflector (Figure 54) is ready to hold two LEDs to generate tunable and circadian illumination. So it will be possible to fill up missing daylight with adequate colour temperature to match the light which is entering through the façade or to activate employees by specific lighting related biological stimuli.

The structure of the ceiling panel is optimized for precisely illuminating the working plane, in daylight as well as artificial lighting session. The structure is rolled with different shapes along its length (Figure 55). For manufacturing and hence costs reasons the alternative of shaping the whole panel is investigated (Figure 56).

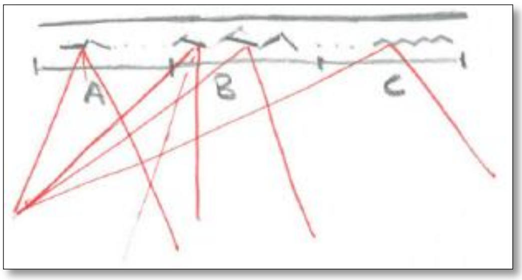


Figure 55 – different zones of planar ceiling panel (Section A, B and C for specifically reflecting onto the task plane in office), preventing glare.

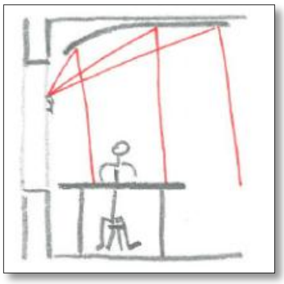


Figure 56 – Different sections in Figure 55 could be approximated by a non-planar panel.

5.2.5 Asymmetric Linear

Mounted (i.e. clicked into the heating/cooling panel) parallel to the façade a symmetric luminous intensity distribution would let a significant amount of light penetrate the façade to the exterior. This well-known problem was already solved with fluorescent tubes but is now to solve with LEDs. The technical realization is based on two already off-the-shelf elements: reflector and lens. First idea was to reshape the square reflector (Figure 57), second, rethink the lens in Figure 58. In both cases light output ratios of >90% are achieved. Optical solutions and manufacturing costs define the final solutions.

Figure 57 – Square reflector

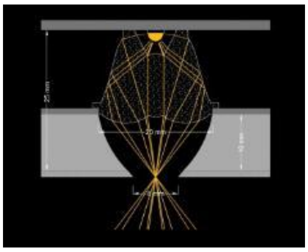
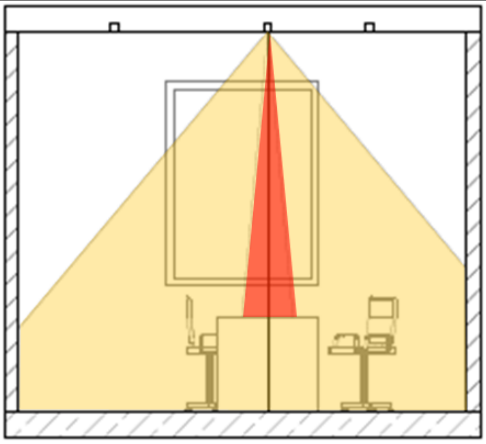


Figure 58 - hole lens

5.2.6 Symmetric linear

linear downlights for subdivision 2 2x40° with additional spotlight main illumination 500lx spot light up to 1000 lx Embedded into ceiling modules via 'click-in' mechanism.	

This solution is ready using the square reflector in Figure 57, alternatively the reflector 'nut' is developed into a linear luminaire for symmetric illumination of subdivision 2 (in Figure 50).

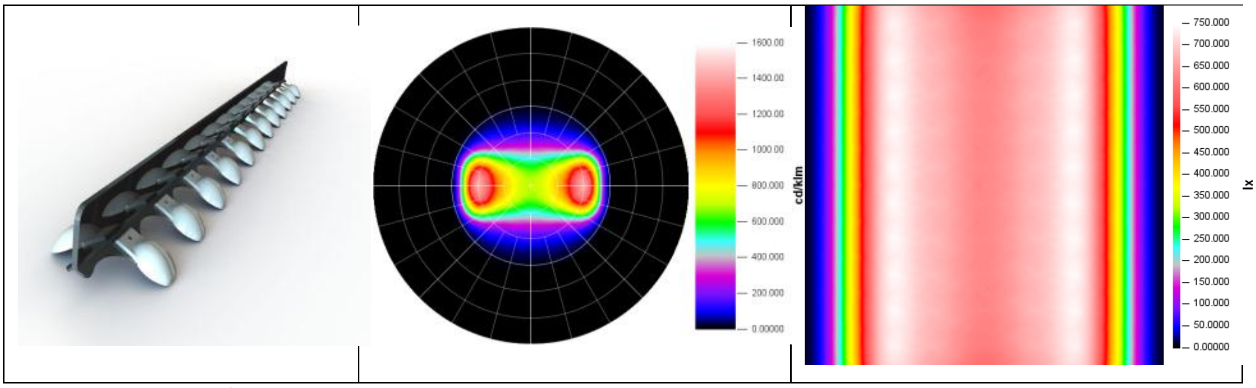
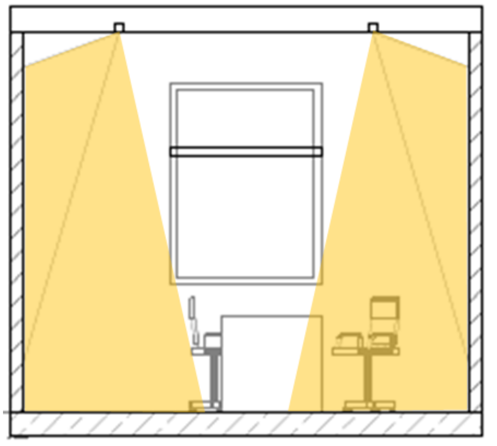


Figure 59 – 'Nut' reflector assembled to a 300 mm luminaire that is illuminating very precise rectangle on the floor or working plane. Luminous intensity distribution and illuminance distribution, if the luminaire is 2m above the plane.

5.2.7 Wallwasher

Wallwasher embedded into ceiling modules E_{vm} ~ 300lx Perpendicular to façade for 1. illuminating walls 2. Illuminating task plane	

This luminaire will be used as wallwasher perpendicular to façade or parallel to the façade as work plane illumination.

5.2.8 Costs

In chapter 3.2 were payback times for single downlights demonstrated; the LED luminaire in comparison to a CFL downlight had a payback time of nearly a decade for a very efficient day lit office (3h/d operating) (see Figure 26). For an office application, where operating hours are around 6 the payback time of this downlight is 4-5 for investments today (in 2013) and 3 years in 2020. This comparison is valid also for other luminaires than downlights, as CFL or LFL luminaires have the same range of efficacies. They are both not able to be dimmable and tunable as LED luminaires are (tunable for daylight or any future - circadian adjustments (i.e. cold or warm white at specific periods of the day)).

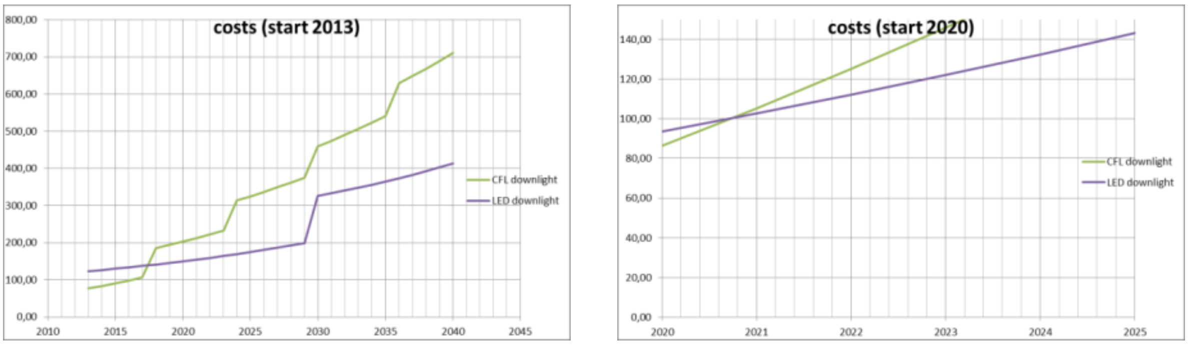


Figure 60 – Payback times for 6h/d operating; a realistic standard office (poorly day lit in comparison to Figure 26.

5.2.9 Control

Based on Bartenbach research results (Weitlaner et al. 2013), the idea is following further enhancing open-loop control strategies with feed forward control ideas and internal small closed-loop elements. Pure open-loop controls (Figure 61) turned out to be too case specific and quite unstable. In the open loop algorithms, an accurate definition of system characteristics is needed for evaluating in time step resolution which control points achieve minimum energy consumptions (e.g. closing the lamella for reduced cooling but increased artificial light. Or let the lamellas open and cool more while there is no need for artificial light). System characterization is still difficult for daylighting devices (i.e. angular dependent transmittance functions) but simple for artificial lighting systems.

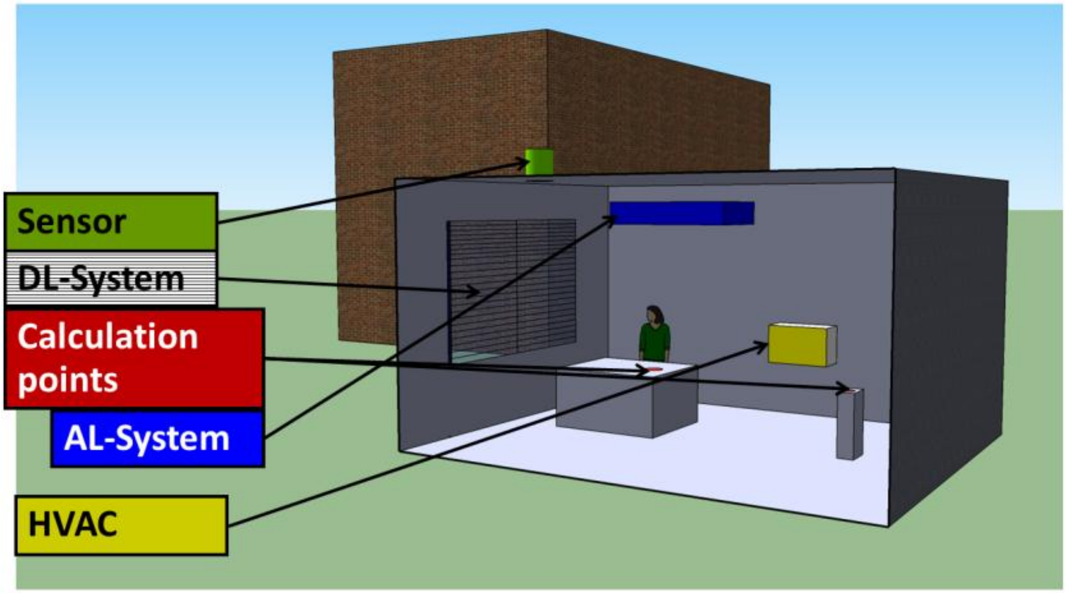


Figure 61 – open loop control scheme for office application

The controls of all luminaires should be possible via wireless communication. Control devices are today available in wireless options for DALI, a 0-10V. Particularly EnOcean (or Zigbee) solutions are checked and implemented where necessary.

Figure 62 - from: http://www.fabolux.com/fabocontrol.html (Oct. 14th 2013)

Conceptual ideas of possible integrating LON control devices:

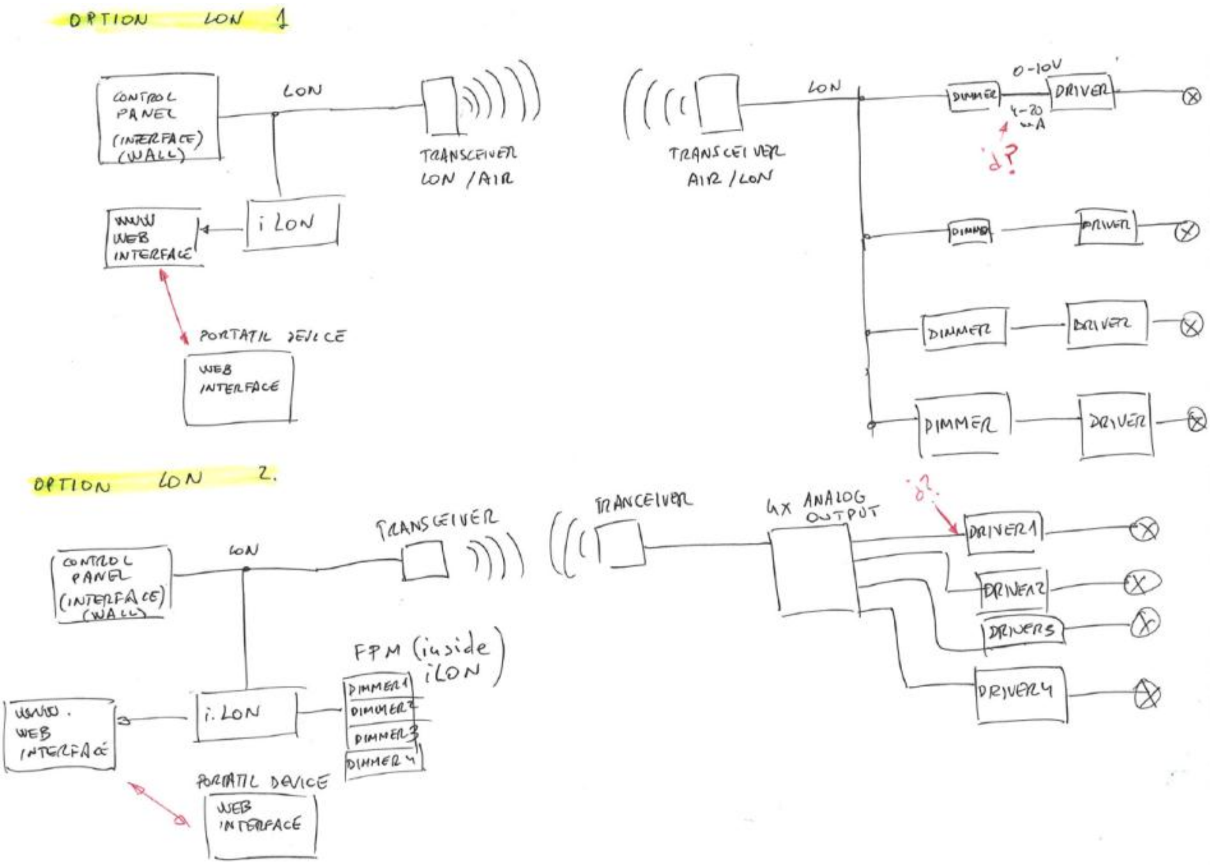


Figure 63 – Control ideas of partner CARTIF for residential application

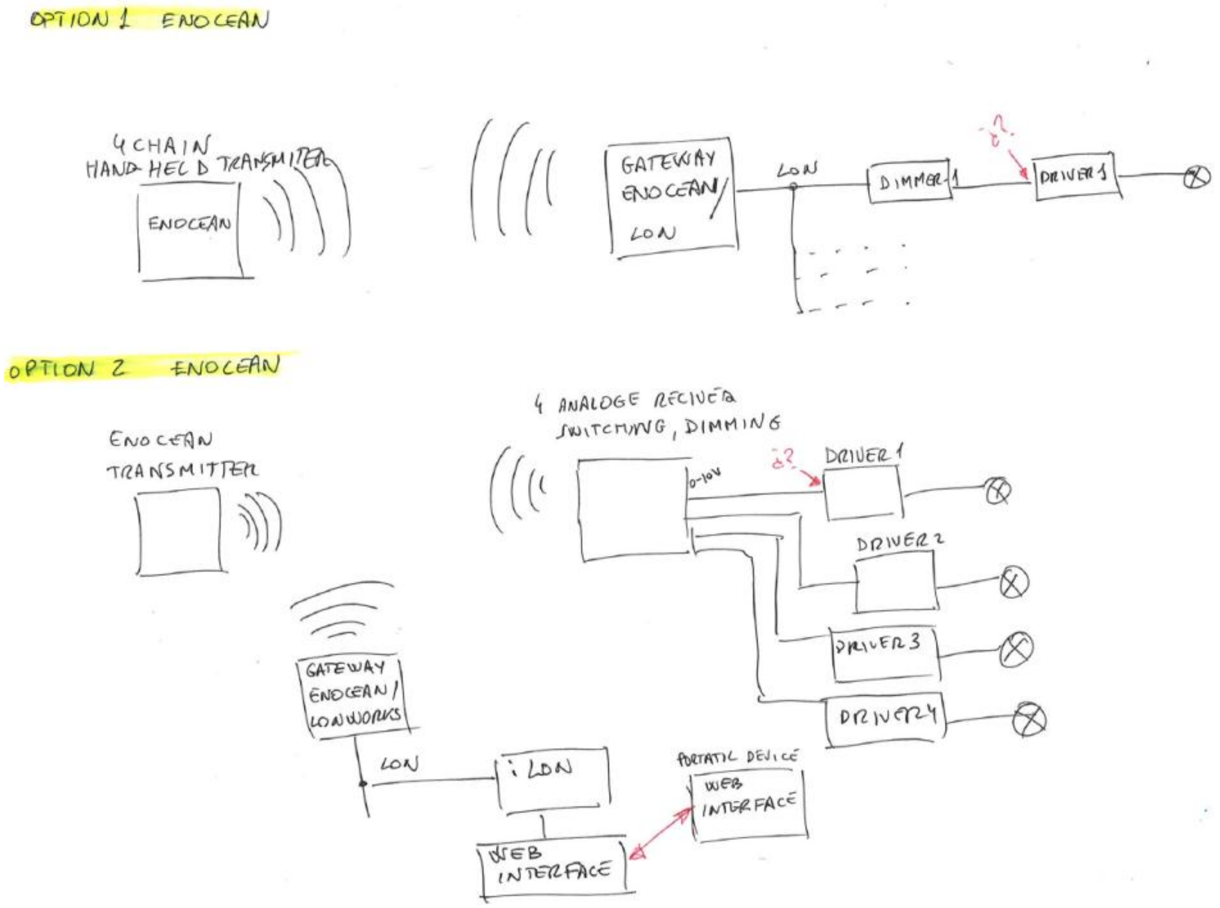


Figure 64 - Control ideas of partner CARTIF for residential application

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